Policy analysis during socio-technical energy transitions: three essays on the Swiss electricity sector

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Abstract

Global energy systems are changing rapidly. This energy transition complicates the use of traditional policy analysis methods. However, proper policy analysis and design is essential in managing the transition. This thesis takes an interdisciplinary approach to analyze three policy issues for the Swiss energy transition, making contributions to policy analysis methodology, sustainability transitions, external governance, as well practical contributions to the governance of the Swiss electricity sector.

The first essay analyzes the impact of the timing uncertainty of the nuclear phase-out. In 2011, the Swiss government decided to phase-out nuclear power but allow the plants to remain online for as long as they can be operated safely, leaving their final operating date uncertain. This decision is analyzed using a system dynamics (SD) simulation model. The results show that the timing uncertainty does not impact the market development or security of supply. However, delaying the nuclear phase-out can have significant advantages for greenhouse gas emissions and security of supply. In all simulated scenarios, Switzerland becomes more dependent on electricity imports.

The second essay analyzes the governance of energy relations between Switzerland and the European Union (EU). Switzerland and the EU have highly interdependent electricity systems, but there is a relatively low level of policy alignment and no formal Swiss-EU electricity agreement. The historical developments in Swiss-EU energy policy are reconstructed through a series of interviews and analyzed using an external governance theoretical framework. Gradual harmonization of EU electricity markets and certain key events have driven Switzerland’s exclusion from EU network governance processes, leading to more hierarchy, reducing Swiss influence on legislative processes, and deteriorating trading conditions. The negotiations for an electricity agreement present an opportunity to reverse this trend, but the future of Swiss-EU bilateralism remains politically uncertain and will depend on general relations more than electricity sectoral dynamics.

The third essay analyzes the Swiss proposal for a strategic energy reserve: a novel policy to increase security of supply in winter, potentially at risk due to the growing import dependency and deteriorating Swiss-EU relations. The policy incentivizes storage operators to keep a minimum amount of energy in reserve, for use in scarcity periods. A new hybrid simulation model is created, combining system dynamics and agent-based modeling. The results show that a strategic energy reserve can improve short-term, but not long-term security of supply. It will likely be cost-ineffective and risks inducing artificial scarcity periods. Any implementation should be done on a dynamic, ad hoc basis, conditional on a short-term adequacy assessment to minimize the costs while increasing the benefits.

The thesis makes several important contributions. It contributes to hybrid and simulation modeling for policy analysis and transitions research. The model offers novel tools for combining short- and long-term market dynamics, opportunity cost bidding, and strategic energy reserves. The findings of each essay are directly relevant for policymakers to inform their decisions about the analyzed policy issues. Finally, the thesis contributes to the theories of sustainability transitions and external governance.

Keywords

Switzerland; energy policy; socio-technical transitions; modeling; electricity market; nuclear phase-out; European Union; external governance; security of supply; strategic energy reserve

Résumé

La transition énergétique complique l'utilisation des méthodes traditionnelles d'analyse des politiques. Cependant, l’analyse des politiques est vitale pour gérer la transition. La thèse analyse de manière interdisciplinaire trois enjeux politiques pour la transition énergétique suisse et apporte des contributions à la méthodologie d'analyse politique, aux transitions durables et à la gouvernance externe, ainsi qu'à la gouvernance de la transition énergétique suisse.

Le premier essai analyse l'impact de l'incertitude de la sortie nucléaire. En 2011, le gouvernement suisse a décidé de sortir l'énergie nucléaire en permettant aux centrales de rester en ligne tant qu'ils peuvent être exploités en sécurité, laissant incertaine leur date d’arrêt finale. Cette décision est analysée avec un modèle basé sur les systèmes dynamiques. Les résultats montrent que l’incertitude n’a pas d’impact sur le marché. Cependant, le report de la sortie nucléaire présente des avantages pour les émissions de gaz à effet de serre et la sécurité d'approvisionnement. Dans tous les scénarios, la Suisse devient plus dépendante des importations d’électricité.

Après avoir identifié l'importance des importations d'électricité dans le premier essai, le deuxième essai analyse les relations énergétiques entre la Suisse et l'UE, qui sont énergétiquement hautement interdépendants, mais politiquement faiblement alignée. L’évolution de la politique énergétique Suisse-UE est élaborée avec une série d'entretiens et analysée à l'aide d'un cadre de gouvernance externe. L'harmonisation progressive des marchés énergétiques de l'UE et certains événements ont entraîné l'exclusion de la Suisse, ce qui a conduit à une hiérarchisation accrue, à une réduction de l'influence de la Suisse et à une détérioration des conditions commerciales. Les négociations d'un accord sur l'électricité représentent une opportunité pour inverser la tendance, mais l'avenir du bilatéralisme Suisse-UE reste politiquement incertain et dépendra davantage des relations générales que des dynamiques sectorielles.

Le troisième essai analyse la proposition suisse de réserve énergétique stratégique, qui vise à garantir la sécurité d'approvisionnement en hiver, potentiellement menacée par la dépendance des importations croissante et la détérioration des relations Suisse-UE. La réserve incite les exploitants de stockage à garder une quantité minimale d’énergie en réserve en cas de pénurie. Un nouveau modèle hybride est créé, combinant la modélisation à base d'agents et des systèmes dynamiques. Les résultats montrent qu'une réserve peut améliorer la sécurité d'approvisionnement à court terme, mais pas à long terme. Elle est peu rentable et risque d’induire des périodes de pénurie artificielle. Toute mise en œuvre devrait être faite dynamiquement, ad hoc, conditionnée à une évaluation des risques à court terme, car cela pourrait minimiser les coûts en augmentant les avantages.

La thèse apporte plusieurs contributions. Elle fait progresser la modélisation des transitions sociotechniques pour l'analyse des politiques, en particulier la modélisation hybride, et offre des outils innovants pour la modélisation des dynamiques du marché à court et à long terme, d'offres de coûts d'opportunité et des réserves d'énergie stratégiques. Les conclusions sont directement utiles pour les décideurs politiques dans leurs décisions au sujet des problèmes politiques analysés. Finalement, elle contribue aux théories des transitions durables et de la gouvernance externe.

Mots-clés

Suisse; politique énergétique; transitions sociotechnique; modélisation; électricité; sortie nucléaire; Union Européenne; gouvernance externe; sécurité d'approvisionnement; réserve stratégique

Zusammenfassung

Die Energiewende erschwert den Einsatz traditioneller Methoden der Politikanalyse. Eine vollumfängliche Bewertung der politischen Instrumente ist jedoch von wesentlicher Bedeutung. Diese interdisziplinäre Dissertation analysiert drei politische Problemfelder, die für die Schweizer Energiewende von besonderer Bedeutung sind. Sie liefert Beiträge zu Methodenentwicklung in der Politikanalyse, der Theorieentwicklung im Bereich von Nachhaltigkeitstransition und externer Governance sowie praktische Beiträge zur Governance der Schweizer Energiewende.

Die erste Studie analysiert die Auswirkungen der Unsicherheit über den Zeitpunkt des Schweizer Atomausstiegs. Im Jahr 2011 hat die Schweizer Regierung beschlossen, aus der Kernenergie auszusteigen, die Kraftwerke jedoch noch so lange in Betrieb zu lassen, wie sie sicher betrieben werden können, wobei das endgültige Betriebsdatum ungewiss bleibt. Die Auswirkungen dieser Entscheidung werden mithilfe eines System Dynamics-Simulationsmodells analysiert. Die Ergebnisse zeigen, dass sich die Unsicherheit über den Zeitpunkt des Ausstiegs nicht auf die Marktentwicklung oder die Versorgungssicherheit auswirkt. Die Verzögerung des Atomausstiegs bringt jedoch erhebliche positive Effekte für die Treibhausgasemissionen und die Versorgungssicherheit mit sich. In allen simulierten Szenarien wird die Schweiz jedoch stärker von Stromimporten abhängig sein.

Die zweite Studie analysiert die Governance der Beziehungen zwischen der Schweiz und der EU im Bereich der Energieversorgung. Das Schweizer und das Europäische Elektrizitätssystem hängen stark voneinander ab. Es besteht jedoch lediglich ein relativ geringes Maß an politischer Angleichung und kein formelles Elektrizitätsabkommen. Die historischen Entwicklungen in der Energiepolitik der Schweiz und der EU werden auf Basis von Interviews rekonstruiert und basierend auf dem theoretischen Rahmen der externen Governance analysiert. Die schrittweise Harmonisierung der EU-Energiemärkte und kritische Schlüsselereignisse haben dazu geführt, dass die Schweiz schrittweise aus dem Europäischen Elektrizitätssektor ausgeschlossen wurde. Dies hat zu einem verstärkt hierarchischen Verhältnis geführt, das den Einfluss der Schweiz auf Gesetzgebungsverfahren verringerte und die Handelsbedingungen verschlechterte. Die Verhandlungen über ein Elektrizitätsabkommen bieten die Möglichkeit, diesen Trend umzukehren. Die Zukunft des schweizerisch-europäischen Bilateralismus bleibt politisch ungewiss und wird mehr von den allgemeinen Beziehungen zwischen den beiden Parteien als von der Dynamik des Elektrizitätssektors abhängen.

Die dritte Studie analysiert den Schweizer Vorschlag für eine strategische Energiereserve: Er umfasst die Einführung eines neuartigen politischen Instruments zur Unterstützung der Versorgungssicherheit im Winter, die möglicherweise aufgrund der wachsenden Importabhängigkeit und der Verschlechterung der Beziehungen zwischen der Schweiz und der EU gefährdet ist. Speicherbetreibern sollen Anreize geboten werden, ein Mindestmaß an Energie für die Nutzung in Zeiten von Knappheit vorzuhalten. Zur Analyse dieses Vorschlages wird in dieser dritten Studie ein neues hybrides Simulationsmodell erstellt, das System Dynamics und agentenbasierte Modellierung kombiniert. Die Ergebnisse zeigen, dass eine strategische Energiereserve die kurzfristige, aber nicht die langfristige Versorgungssicherheit verbessern kann. Dies ist wahrscheinlich nicht kostengünstig und birgt das Risiko, künstliche Knappheitsperioden auszulösen. Es zeigt sich darüber hinaus, dass jegliche Implementierung einer solchen strategischen Reserve auf einer dynamischen Basis erfolgen und von einer kurzfristigen Beurteilung der Angemessenheit abhängig gemacht werden sollte, um die Kosten möglichst gering zu halten und gleichzeitig den Nutzen zu steigern.

Mit diesen drei Studien, leistet die vorliegende Dissertation mehrere wichtige Beiträge: Zum einen trägt sie entscheidend zur Entwicklung von Hybrid- und Simulationsmodellierung für die Politikanalyse und Übergangsforschung bei. Das erarbeitete Modell bietet neuartige Tools zur Kombination von kurz- und langfristiger Marktdynamik, Opportunitätskosten und strategischen Energiereserven. Zum anderen sind die Ergebnisse jeder Studie aber auch direkt für politische Entscheidungsträger relevant, um ihren Entscheidungen über die analysierten politischen Fragen eine wissenschaftliche Fundierung zur Verfügung zu stellen. Schließlich trägt die Dissertation auch zur Theorieentwicklung von Nachhaltigkeitstransitionen und externer Governance bei.

Schlagworte

Schweiz; Energiepolitik; soziotechnische Transition; Modellierung; Strommarkt; Atomausstieg; Europäische Union; externe Governance; Versorgungssicherheit; strategische Energiereserve

Samenvatting

Wereldwijd zijn energiesystemen in transitie. Deze energietransitie bemoeilijkt het gebruik van traditionele methodologie voor beleidsanalyse, maar tegelijkertijd is beleidsanalyse is essentieel voor het succes van de transitie. Dit interdisciplinaire proefschrift analyseert drie beleidskwesties voor het Zwitserse energiebeleid en levert daarmee academische bijdragen aan de methodologie voor beleidsanalyse, duurzaamheidstransities, en externe governance, evenals praktische bijdragen aan het Zwitserse energiebeleid.

Het eerste essay analyseert de onzekerheid omtrent het sluiten van de kerncentrales. In 2011 besloot de Zwitserse regering om kernenergie uit te faseren, maar de bestaande centrales te laten opereren zolang dat veilig wordt geacht. De definitieve sluitingsdata blijven daarmee onzeker. Deze beleidskeuze wordt geanalyseerd met behulp van een simulatiemodel op basis van systeemdynamica. De resultaten tonen dat de onzekerheid geen invloed heeft op de marktontwikkelingen. Echter, uitstel van de sluitingsdata kan voordelen meebrengen voor de uitstoot van broeikasgassen en de netstabiliteit. De resultaten tonen daarnaast dat Zwitserland meer afhankelijk zal worden van geïmporteerde elektriciteit na het sluiten van de kerncentrales, in het bijzonder in de winter.

De elektriciteitshandel is daarmee belangrijk voor het succes van de energietransitie in Zwitserland. Het tweede essay analyseert daarop de Zwitsers-Europese energierelaties. Zwitserland en de EU zijn onderling sterk afhankelijk, maar hebben relatief weinig beleidscoördinatie op het gebied van energie. De historische ontwikkelingen omtrent het energiebeleid van Zwitserland en de EU worden in het essay uitgezet op basis van interviews en met een theoretisch kader van externe governance geanalyseerd. De harmonisatie van de Europese energiemarkten en bepaalde sleutelmomenten hebben Zwitserland geleidelijk buitengesloten van Europese beleidsprocessen, met als gevolg meer hiërarchie en verslechterende handelscondities. Een elektriciteitsovereenkomst biedt een kans om deze trend te keren, maar de toekomst van het Zwitsers-Europees bilateralisme is politiek onzeker en zal meer afhangen van algemene Zwitsers-Europese betrekkingen dan de dynamiek in de elektriciteitssector.

Het derde essay analyseert het Zwitserse voorstel voor een strategische energiereserve: een nieuw beleidsinstrument om de netstabiliteit in de winter te ondersteunen, als direct gevolg van de groeiende afhankelijkheid van elektriciteitsimport en de verslechterende betrekkingen met de EU. Het beleid stimuleert elektriciteitscentrales om een minimale hoeveelheid energie in reserve te houden voor kritische periodes. Voor de analyse wordt een hybride simulatiemodel ontwikkeld dat systeemdynamica en agent-gebaseerd modelleren combineert. Uit de simulaties blijkt dat een strategische energiereserve de netstabiliteit op de korte termijn kan verbeteren, maar geen voordelen brengt op de lange termijn. Daarnaast is het waarschijnlijk niet kosteneffectief en kan het kritische perioden in de energievoorziening veroorzaken. Als een strategische energiereserve wordt geïmplementeerd, zou het conditioneel moeten zijn aan een dynamische, ad-hoc beoordeling van de netstabiliteit om de kosten te minimaliseren en de voordelen te vergroten.

Het proefschrift maakt verschillende contributies. Simulatiemodellering, en specifiek hybride modellering, wordt als methode voor beleidsanalyse en transitiesonderzoek bevordert. Het proefschrift biedt nieuwe methodes voor het combineren van marktdynamiek op korte en lange termijn, het modelleren van strategische energiereserves en bieden in energiemarkten op basis van opportuniteitskosten. De bevindingen zijn daarnaast direct relevant voor beleidsmakers in hun beslissingen omtrent de geanalyseerde beleidskwesties. Tenslotte draagt het proefschrift bij aan de theorieën over duurzaamheidstransities en externe governance.

Trefwoorden

Zwitserland; energiebeleid; socio-technische transities; modelleren; elektriciteitsmarkt; kernuitstap; Europese Unie; external governance; netstabiliteit; strategische energiereserve

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List of abbreviations and acronyms

ABM	- Agent-Based Modeling
ACER	- Agency for the Cooperation of Energy Regulators
AFMP	- Agreement on the Free Movement of People
BABS	- Bundesamt für Bevölkerungsschutz (*Swiss Federal Office for Civil Protection*)
BAU	- Business as Usual
BFE	- Bundesamt für Energie (*Swiss Federal Office of Energy*, c.f. SFOE)
BL	- Baseline
CCGT	- Combined Cycle Gas Turbine
CEER	- Council of European Energy Regulators
CEP	- Clean Energy Package
CHF	- Swiss Franc
CO_2	- Carbon Dioxide
DR	- Demand Response
DSO	- Distribution System Operator
EC	- European Commission
EEA	- European Economic Area
ElCom	- Eidgenössischen Elektrizitätskommission (*Swiss Federal Electricity Commission*)
EMG	- Elektrizitätsmarktgesetz (*Electricity Market Law*)
ENSI	- Eidgenössisches Nuklearsicherheitsinspektorat (*Swiss Federal Nuclear Safety Inspectorate*)
ENTSO-E	- European Network of Transmission System Operators for Energy
EPEX	- European Power Exchange
ERGEG	- European Regulators Group for Electricity and Gas
ES50	- Energy Strategy 2050
ETSO	- Association of European Transmission System Operators
EU	- European Union
FOR	- Forced Outage Rate
GDP	- Gross Domestic Product
GHG	- Greenhouse Gas
GME	- Gestore dei Mercati Energetici (*Italian Energy Market Operator*)
GWh	- Gigawatt-hour
IEA	- International Energy Agency

IEM - Internal Energy Market

IPCC - Intergovernmental Panel on Climate Change

IRR - Internal Rate of Return

ITC - Inter-TSO Compensation

kW - Kilowatt

kWh - Kilowatt-hour

LTC - Long-term Contract

MLP - Multi-level perspective

MT - Megaton (10^9 kilogram)

MW - Megawatt

MWh - Megawatt-hour

NC - Network Code

NGCC - Natural Gas Combined Cycle

NOAA - National Oceanic and Atmospheric Administration

NPV - Net Present Value

NREL - National Renewable Energy Laboratory

NTC - Net Transfer Capacity

PV - Photovoltaic

RES - Renewable Energy Sources

RTE - Réseau de Transport d'Électricité (*French Electricity Transmission System Operator*)

SD - System Dynamics

SER - Strategic Energy Reserve

SFOE - Swiss Federal Office of Energy (c.f. BFE)

STRN - Sustainability Transitions Research Network

StromVG - Stromversorgungsgesetz (*Electricity Supply Act*)

TC - Ton of Carbon (10^3 kilogram CO_2)

TSO - Transmission System Operator

TWh - Terawatt-hour

UCPTE - Union for the Coordination of Production and Transmission of Electricity

UCTE - Union for the Coordination of Transmission of Electricity

UNFCCC - United Nations Framework Convention on Climate Change

VOLL - Value of Lost Load

VSE - Verband Schweizerischer Elektrizitätsunternehmen (*Swiss Association of Electricity Producers*)

WACC - Weighted Average Cost of Capital

Chapter 1 Introduction

The subject of this thesis is policy analysis during socio-technical energy transitions. Modern energy systems are changing rapidly, with the aim of becoming more environmentally sustainable while at the same improving or at least preserving economic and social sustainability. Governments play an important role in this socio-technical transition. Policies need to be implemented to ensure that the energy transition is managed in a fair and secure manner, as energy systems enable the functioning of all aspects of our society and cannot be put at risk. These policies will need to be properly designed, and policy analysis is therefore vital. However, the novelty of the challenges and the transitional state of the energy system complicate the use of traditional policy analysis methods, which often rely on the extrapolation of historic policies or on idealized assumptions such as market equilibrium.

This thesis approaches three distinct policy issues of the electricity sector in Switzerland from a pragmatic perspective, aiming to contribute both substantively to the management of these policy issues as well as academically to advance theory and methodology of policy analysis for socio-technical and sustainability transitions. The first policy issue is the timing uncertainty of the Swiss nuclear phase-out. The second energy policy issue is the governance of Swiss-EU energy relations. The third policy issue is the Swiss proposal for a strategic energy reserve.

The first part of this chapter (section 1.1) will describe the motivation for this thesis in more detail and provide the necessary background information on transitions, types of policies, policy analysis, and Swiss energy policy. The three policy issues will be introduced and placed in a single context. Section 1.2 details the research philosophy underlying this thesis. Chapter 2, Chapter 3, and Chapter 4 respectively contain the analysis of the three energy policy issues in Switzerland. These chapters have each been published as stand-alone articles and are intended to be able to be read as such. They therefore each contain introductions and conclusions, and some repetition is to be expected in these sections as they treat related subjects. The fifth and final chapter of the thesis contains a critical reflection on each of the three studies individually as well as together. The substantive, theoretical, and methodological contributions of this thesis are summarized, and some perspectives are given for future research.

1.1 Motivation

This section is divided into four sections. The first section (1.1.1) discusses socio-technical systems and transitions. The importance of policy analysis and design is explained in relation to academic theories of sustainability transitions. The second section (1.1.2) will provide a definition for the different types of policy. It will become clear why the energy transition requires the design of new policies. The third section (1.1.3) will describe the fundamentals of policy analysis and how the energy transition places new challenges on traditional policy analysis methodologies. The last section (1.1.4) introduces the three central policy issues of the thesis by giving the necessary background information on the Swiss energy transition.

1.1.1 Energy systems in transition

Society has experienced several energy transitions in the past: from biomass (wood) to solid fossil fuels (coal) and then to liquid fossil fuels (oil and gas). Figure 1.1 shows the historical energy transitions that have occurred in the Germany. Most developed countries have experienced similar transitions, with coal generally peaking in the early 20th century and nuclear and renewable slowly arriving in the last few decades. The energy transitions of the past were driven mainly by technological and economic advantages. Coal was cheaper and had a higher energy density than wood, while oil and gas served more technological purposes and could be more easily transported than coal. The sustainable energy transition is about phasing out fossil fuels in favor of sustainable energy sources. The early traces of this transition can already be seen in Figure 1.1. As Grubler (2012) points out, the historic transitions, or at least the 20th century transition that substituted coal for oil, gas, and electricity in large parts of the economy, also resulted in decarbonization, as coal is far more polluting than oil and gas.

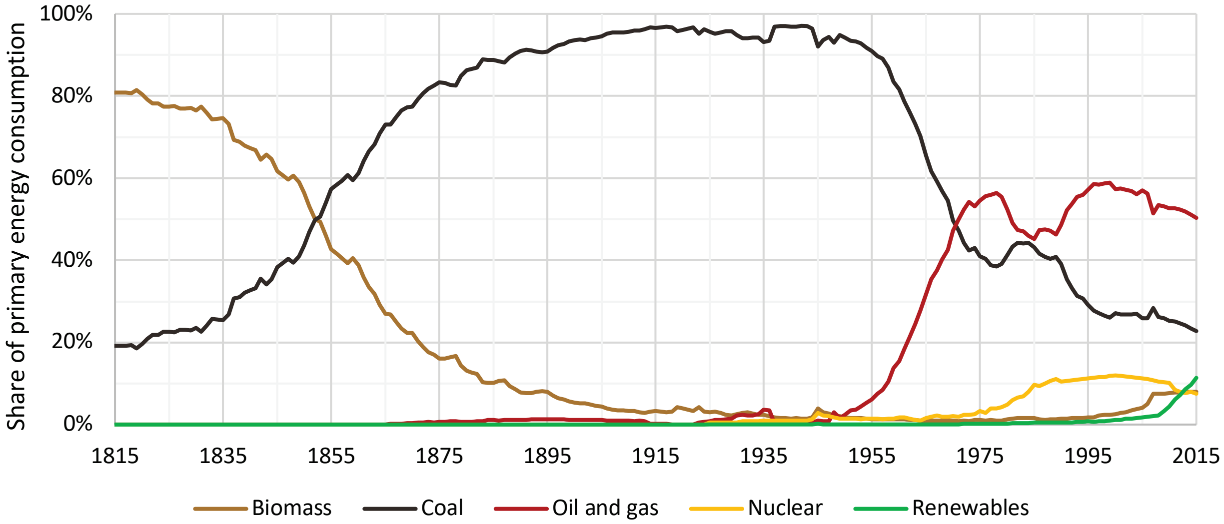

Figure 1.1: Energy transitions in Germany 1815-2015. Author elaboration. Source: AGEB (n.d.).

Unlike the historical energy transitions, the sustainable energy transition is not purely driven by an economic or technological rationale, but primarily by diverse normative motivations which include the environment, geopolitical security, and public health. Initial signs of the necessity of this transition came not from an economic or technological advancement, but from influential environmental theories like Hubbert's peak oil theory (Hubbert, 1967), alarming the world about the finiteness of fossil fuels, or the Club of Rome's infamous Limits to Growth (Meadows, Meadows, Randers, & Behrens, 1972), highlighting how thin the resources of this planet are being stretched because of exponential population growth. In recent decades, the linking of fossil fuel consumption to climate change and the discovery of the severity of climate change's potential impacts (IPCC, 2014) has given a new impulse to the sustainable energy transition.

The energy system, which includes the electricity system, is integral to nearly every aspect of modern society and fulfills the characteristics of a so-called socio-technical system (Geels, 2004), and the current configuration of the energy system, based largely on fossil fuels, that of the dominant or incumbent socio-technical regime (Berkhout, Smith, & Stirling, 2004). Socio-technical transitions, then, are generally understood as large-scale transformations or "fundamental shifts" (Markard, Raven, & Truffer, 2012, p. 955) of such systems. Rotmans et al. offer a more elaborate definition: "a gradual, continuous process of change where the structural character of a society (or a complex sub-system of society) transforms [involving] a range of possible development paths, whose direction, scale and speed government policy can influence, but never entirely control" (2001, p. 16). This definition explicitly acknowledges the role of policy in this process. Government policy is not the driving force behind a transition and can merely seek to manage or influence the process.

The study of sustainability transitions, or socio-technical transitions towards sustainability, has arguably emerged from a sub-discipline of socio-technical transition theory into an academic field of research on its own (Markard et al., 2012), with a large number of publications to support it. However, sustainability transitions are generally still included within the larger group of socio-technical transitions. The core strands of "transition theory" can be roughly divided into 4 areas (Markard et al., 2012): strategic niche management (Kemp, Schot & Hoogma, 1998; Rip & Kemp, 1998), the multi-level perspective (Geels, 2002), technological innovation systems (Bergek et al., 2008; Edquist, 1997; Hekkert et al., 2007), and transition management (Rotmans et al., 2001). Arguably, the most influential of these and the most relevant to this thesis is the multi-level perspective (MLP).

The MLP categorizes society into three distinct levels (Figure 1.2): the landscape, the regime, and the niche. Geels refers to these levels as "analytical and heuristic concepts" used to understand transition dynamics, rather than "ontological descriptions of reality" (2002, p. 1259), meaning the levels and their boundaries are not always clearly identifiable in society. The landscape describes the exogenous context, comprised of macro-political, macro-economic, environmental, and deep-rooted cultural factors. Regimes are the dominant mode of organization of a socio-technical system (Rip & Kemp, 1998). Niches are protected spaces outside of the regime supported by small networks of actors where experimentation can occur, and innovations can develop. Landscape factors put pressure on regimes, creating windows of opportunities, providing chances for niches to develop. Such pressure can come in the form of a "shock" but can also be a more gradual process. Transitions thus occur at the regime level, by fundamentally changing or replacing the incumbent regime. Many studies have focused on identifying so-called transition 'pathways' and 'contexts' in which transitions occur. Smith et al. (2005) offer a typology of such transition contexts as a function of two key characteristics: the level of coordination that the incumbent regime exhibits responding to pressure, and the locus of the resources that the incumbent regime needs to adapt to pressure (internal or external to the regime, see Figure 1.3).

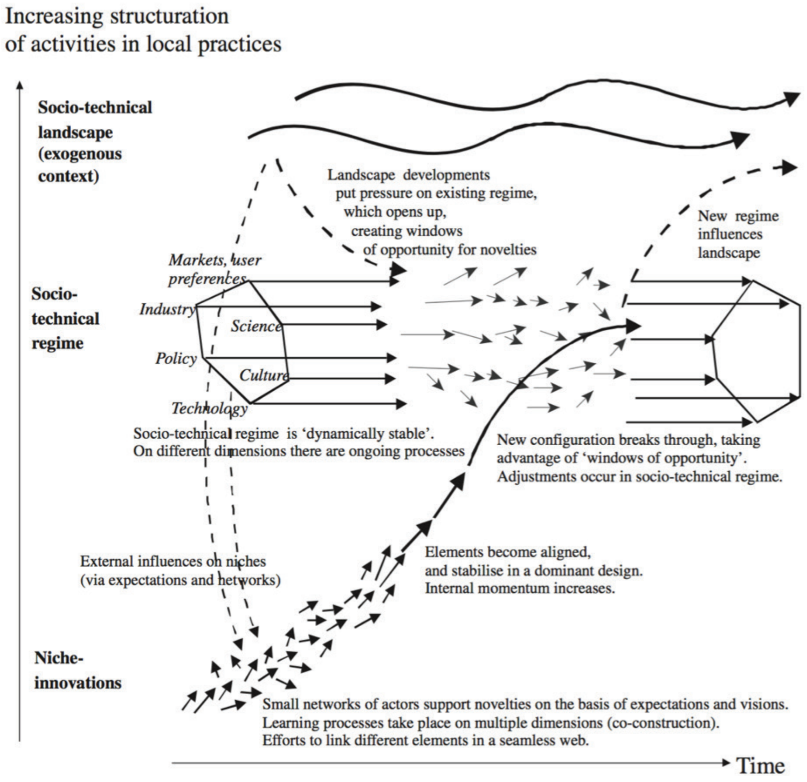

Figure 1.2: Transitions in the multi-level perspective. Source: Geels, 2012, p. 474. Reprinted with consent of copyright holder.

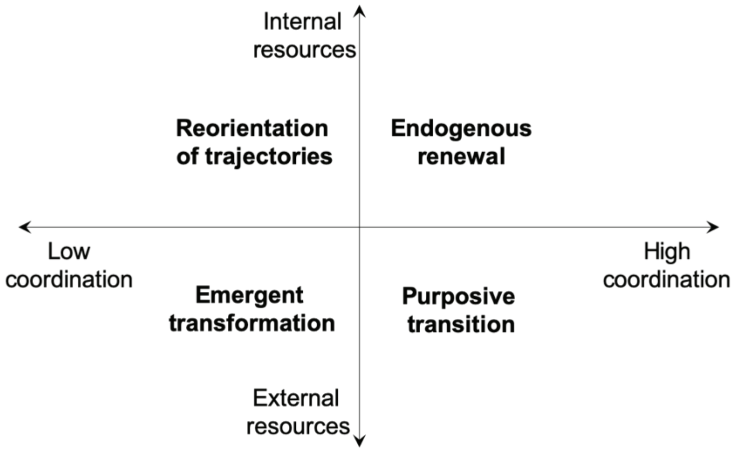

Figure 1.3. Typology of transition contexts. Adapted from Berkhout et al., 2004, p. 67.

Geels and Schot (2007) offers a different typology, focusing instead on the presence of niche innovations and the nature of the pressure driving the transition as the key differentiator of the transition pathways. They identify four pathways: transformation, reconfiguration, de-alignment and re-alignment, and substitution. In the *transformation pathway*, there is moderate pressure for the regime to change coming from the landscape level, but no niche innovation has developed sufficiently or closely enough to the regime. The incumbent regime adapts to respond to the pressure, leaving the basic architecture intact. The *reconfiguration pathway* is similar, but niche innovations that are 'symbiotic' to the regime are present in society at the time of the pressure. The niche innovations are adopted as part of the regime to deal with the pressure. Over time, these niches develop and trigger further adjustments in the structure of the regime. In contrast, the *de-alignment and re-alignment pathway* does not see moderate pressure but rather a sudden, heavy pressure or 'shock', while no clearly superior niche innovation exists yet. The regime 'falls apart', creating a period of uncertainty where multiple niche innovations compete for dominance. Eventually, a single niche will manage to develop, stabilize, and form a new regime. The *substitution pathway* is similar. However, at the time of the sudden pressure and subsequent "window of opportunity", a niche innovation is already adequately developed to substitute the regime, resulting in much less disruption. In this last pathway, the pressure does not have to come from the landscape level alone, but can also come from the niche itself, pressuring the regime from below and creating its own opening.

The above description of the MLP and the various transition pathways explains how transitions occur but leaves out a coherent conceptualization of politics, power, and agency, an often heard criticism (Avelino & Wittmayer, 2016; Geels, 2011; Verhoog, 2018). Transitions are conceptualized to occur in the presence of pressure, but the theory does not adequately explain who or what is at the origin of that pressure, why, or how that pressure materializes, leaving little room to explore policy processes or governance mechanisms. Geels (2014) tried to address these concerns but chose to focus on power as the expression of a regime's resistance to change, rather than power as a driver of transitions, leaving most of these questions open.

Transition management, one of the other major strands of research in transition theory, somehow bridges this gap by focusing more on the active role of governance. It is an explicitly normative and prescriptive framework and has seen wide range of studies and real-world applications, with varying success (Bergh & Bruinsma, 2008; Heiskanen, Kivisaari, Lovio, & Mickwitz, 2009; Loorbach & Rotmans, 2010; Loorbach, Van Der Brugge, & Taanman, 2008; Wittmayer, Steenbergen, Rok, & Roorda, 2016). It provides an operational policy model, a set of guiding principles focusing on stakeholder inclusivity and continuous policy adjustments based on ongoing evaluation of implemented policies and changes in society. As such it tries to link long-term planning to short-term policy cycles (Loorbach, 2010). Transition management recognizes that policy analysis and design is important in all stages of the transition, vital for monitoring implemented policies, analyzing their impacts, redesigning or removing existing policies, and implementing new policies. As it focuses more on the policy process, which the MLP largely overlooks, it can be seen as complementary to the MLP rather than competing with it.

1.1.2 Policies and instruments

The previous section explained energy transitions and the role of policies in them. This section will describe what a policy is and what types of policies and instruments exist. Policy as a concept is widely used in the academic literature in many different fields. As such, it is not easy to give a single definition. In political sciences, one of the more classic definitions of policy is offered by Lasswell: "the most important choices made either in organized or private life" (Lerner & Lasswell, 1951, p. 5). This definition is easy to understand and leaves ample room for interpretation. A more technical definition is offered by Walker: "the set of forces within the control of the actors in the policy domain that affect the structure and performance of the system" (2000, p. 13). Bridgman and Davis (2000) bring the concept of policy closer to the concept of governance and presuppose some authority in making choices, describing policy as “the instrument of governance, the decisions that direct resources in one direction but not another”. They go on to describing policies in a myriad of ways, including as “the objective of governmental action” and as the “authoritative choice of a government”. These definitions all convey some active, intentional, part on behalf of the government. Klein and Marmor offer a broader definition, stating that policy is simply “what governments do and neglect to do” (2006, p. 892), which allows for policies and their consequences to be unintentional as well.

A slightly more functional approach to defining policy would be to offer an operationalized description. According to Hall (1993), policy change happens on three different levels. The first level or *order* of policy change is concerned with policy settings, meaning the height or level of policy instruments. First order policy changes maintain the basic functioning of policy instruments and are as such associated with incremental change and routinized decision-making. The second level of policy change is about changing or selecting policy instruments. Second order changes are more closely related to strategic action and decision-making. Third order policy change then, is about selecting policy goals or objectives, or the hierarchy of such goals. The problem of climate change can be used to illustrate these levels in the context of this thesis. For policymakers, mitigation can be chosen as an important objective or strategy in response to climate change (third order policy). An instrument in accordance with this objective could then be a carbon tax (second order policy). Finally, the height or level of the tax needs to be set (first order policy). Hall observes that third order changes, which he also refers to as ‘paradigm shifts’, are highly infrequent, while first order changes happen more regularly. Higher orders of policy change are impacted by ideological, political and sociological processes, while lower orders of change are less controversial and are often approached more scientifically.

In the context of sustainability transitions, most of the policy changes can be considered of the third order (Verbong & Geels, 2010), at least during the initial phases of the transition. As described in the previous section, sustainability transitions are about socio-technical regime change. This involves changing the hierarchy of policy goals such as environmental sustainability, economic growth, and social justice. Many transition studies therefore look at how such third order change can be or has been achieved. However, first and second order policy changes are at least as important for a successful energy transition as third order policy changes, as third order policy changes cannot exist in isolation if they are to have any impact. Since one of the primary policy goals of the sustainable energy transition—decarbonization, or more broadly, climate change mitigation—is new and has no historical equivalency, many of the policy instruments are as novel as the third order policy changes that they accompany.

The three essays in this thesis each look at a policy issue related to a different order of policy. The first essay (Chapter 2) analyzes a first order policy: the timing of the Swiss nuclear phase-out. The second essay (Chapter 3) deals with the historical evolution of Swiss-EU energy policy and governance, which can be considered third order change, as it analyzes how overall priorities and governance patterns have changed. The third and last essay (Chapter 4) evaluates a new policy instrument, the strategic energy reserve, and therefore focuses on a second order policy change. However, some of the strategic energy reserve design parameters are also evaluated, which would be considered first order policies.

1.1.3 Policy analysis

The previous sections explained what policies are and what role they have in the sustainable energy transition. This section will explain the fundamentals of policy analysis. Policy analysis can be defined as "a set of systematic procedures […] to attack contemporary policy problems" (Patton, Sawicki, & Clark, 2012, p. 3) or "a rational, systematic approach to support policymaking" (Walker, 2000, p. 12). These two definitions are quite similar, and they each show the essential features of policy analysis. First, policy analysis is a systematic set of procedures or methodologies, second, it is problem oriented, and third, it is used to support policy actors in their decisions. Bardach (2011) offers one of the most complete sets of such 'systematic procedures' for policy analysis. He describes policy analysis as a process with eight steps. The first step is to define the problem, then assemble some evidence, construct the alternatives, select the criteria, project the outcomes, confront the trade-offs, decide, and finally, tell the story. While the full eight steps are a useful way of structuring research for policy analysts, the terms policy analysis 'tool' or 'method' commonly only refer to the fifth step: projecting (or evaluating) the outcomes of policies.

Policy analysis tools can be categorized along many different axes. A popular categorization of policy analysis methods, or research methods in general, is qualitative versus quantitative. Another often-used categorization is *ex post* versus *ex ante*. *Ex post* policy analysis evaluates a policy after it has been implemented, to "produce a stamp of success or failure" (McConnell, 2010, p. 347). A detailed analysis of the case can reveal which specific factors contributed to its success or failure, which can help policy makers when deciding about similar policies in the future. Such *ex post* analyses are often done quantitatively using statistical and econometric analysis on key metrics, especially on first and second order policy changes, or qualitatively using in-depth case studies to explore more complex relationships and impacts. In contrast, *ex ante* analysis evaluates the likely impact of proposed policies before they have been implemented. Since a full experimental setup is usually not possible when dealing with policies[1], researchers often have to rely on models and frameworks, both qualitatively and quantitatively. A model, as I use the term in this thesis, refers to a "simplified, stylized, and formalized representation[s] of (a part of) reality" (Holtz et al., 2015, p. 43). *Conceptual* models describe the most important concepts and ideas of the modeled reality, and how they relate. *Formal* models build on top of a conceptual model and operationalize the concepts and ideas so that they can be manipulated and explored in study. Formalized models are often, but not

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[1] While society is rarely used a laboratory for policy experiments, governments sometimes experiment with different policies in small regions, testing out what works and what does not, before implementing a policy nationally.

exclusively, built with the aid of computer programming or other software tools. Models can be highly tailored to a single case or model more general aspects of reality. Since all models necessarily abstract from reality, there is no such thing as a "perfect" model, and all results will inherently be unfalsifiable (Sterman, 2000). However, the abstracted reality in models allow for all kinds of manipulation, including the introduction of policies and the evaluation of their impact. As such, models provide a way of experimenting with policies before implementing them in reality.

In relation to transition studies, one of the most common policy analysis methods is the qualitative case study (Markard et al., 2012), often in combination with a theoretical framework such as the multi-level perspective or the transition pathways approach as described in section 1.1.1. This has been a popular approach because it allows for the type of in-depth analysis of complex mechanisms often present in socio-technical transitions and third order policy changes. Policies are analyzed in these case studies using a wide range of available data, publications, and sometimes supplemented by the use of interviews. While the MLP and the transition pathways approach has been quite popular, they have not been without substantial criticism from other scholars (Geels, 2011; Genus & Coles, 2008; Smith, Voß, & Grin, 2010). The criticism tends to focus on the fact that the MLP studies have not been systematically done in the same way, making it impossible to lend credit to the framework as a whole, and that there has been a general tendency to focus on *ex post* analyses of already "winning" niches and successful transitions, biasing the results (Smith et al., 2010) and limiting its generalizability to future transitions. Furthermore, the pathways approach has been described as too neat, oversimplifying the perceived effect of individual governance policies aimed at reinforcing certain forces—according to critics, policies can have many more unintended side-effects than the MLP framework dictates, and the MLP fails to recognize this (Genus & Coles, 2008).

The last common criticism of the MLP and transitions perspective is most relevant for this study. Even though a transitions perspective can be comprehensive and has been useful in structuring *ex post* policy analyses, it does not provide quantitative insights and offers limited ability to perform *ex ante* analysis, as it offers only a descriptive, qualitative framework. Transition dynamics are often highly unique and *ex post* analyses offer only limited support for future policy decisions. In response, some researchers have called for and attempted to combine a transitions perspective with quantitative modeling and simulation (Holtz et al., 2015; Papachristos, 2011, 2014; Safarzyńska, Frenken, & van den Bergh, 2012). Papachristos (2014) names three reasons: first, quantitative modeling can analyze the complex interactions and feedback effects that are inherent in socio-technical transitions, and their timing in particular. Second, simulation can integrate multiple systems' approaches, methods, and tools in transition research. Because socio-technical transitions are by definition complex and unpredictable, Papachristos argues that understanding their dynamics necessarily requires more than human cognition. Lastly, quantitative simulation provides practical results that can directly support policy makers, which is particularly relevant since the need for transition research is not purely academic but also very urgent and practical (Papachristos, 2014, p. 1038). From the reasons that Papachristos provides, it is clear why a transition perspective offers valuable insight for this thesis, but a variety of other methods including simulation and modeling will be necessary to make relevant and practical contributions for certain policy issues. Of the various types of simulation, system dynamics and agent-based modeling are often cited as having the most potential for sustainability transitions (Köhler et al., 2019, p. 19).

The three essays in this thesis treat different policy issues, and subsequently, the policy analysis method is different in each of them. For the first and second order policy issues (Chapter 2 and Chapter 4, respectively), quantitative modeling and simulation is used for an *ex ante* policy analysis. As described above in section 1.1.2, lower order policy issues are less socio-political or ideological than higher order policy issues and are therefore more suited to be approached quantitatively. The first essay uses a single-paradigm system dynamics model, while the third essay uses a hybrid agent-based system dynamics model. The second essay (Chapter 3) is an *ex post* policy analysis of a third order policy issue. Quantitative simulation would not lead to insightful findings in this case. Instead, the essay contains an in-depth qualitative analysis relying on interview and documentary data and applying a theoretical framework.

1.1.4 Energy policy in Switzerland

Each of the three essays in this thesis contain their own introduction to the specific policy issue that they analyze. This section will provide an overview of the Swiss energy transition, placing the three studies into a single context, while reviewing some of the academic works on Swiss energy policy.

Switzerland's electricity system is one of the most sustainable and least carbon-intensive of the developed world (IEA, 2018), largely owing to the high penetration of hydro- and nuclear power. Switzerland has no large fossil fuel power plants, but theoretically allows for such plants to be built as long as they fully offset their CO_2 emissions[2]. The future of nuclear power in Switzerland, however, is finite. The first nuclear power plant came into operation in Switzerland in 1969 and today five reactors are in operation (ENSI, 2019), providing slightly over a third of Swiss electricity (SFOE, 2018c). Between the early eighties and 2011, five referenda were held to limit the development of nuclear power, none of which were successful (Ochoa & van Ackere, 2009). The last of these, the *Electricity Without Nuclear* initiative of 2003, was still opposed by two-thirds of Swiss voters. However, the nuclear disaster at the Fukushima Daiichi nuclear power station in 2011—one of the biggest nuclear disasters the world has ever seen (Lelieveld, Kunkel, & Lawrence, 2012)—provided the Swiss federal government with enough political capital to push through a gradual nuclear phase-out. According to the International Energy Agency (IEA), public opinion right before the accident was already split nearly in the middle. Since any new licenses for nuclear power plants would have been subject to referenda, it would have been unlikely that after the accident any license would be

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[2] Offsets are a costly business in Switzerland. Federal law dictates at least 50% of the offsets have to come from domestic mechanisms (Swiss Confederation, 2018, p. 96). Offsetting is generally about three to five times more expensive within Switzerland than abroad (Foundation myclimate, n.d.), and carbon storage for offsetting might face significant social acceptance issues domestically (Volkart et al., 2016).

approved, even if the government would have theoretically allowed it (IEA, 2012). The government did not set a deadline for the country to part with nuclear power, such as for instance Germany did in response to the disaster (Bruninx, Madzharov, Delarue, & D'haeseleer, 2013), but chose to only prohibit the licensing of new power plants while allowing the existing nuclear reactors to remain connected to the electricity grid as long as they can be operated safely. The policy decision to leave the exact timing of the phase-out undecided is the subject of the first study in this thesis (Chapter 2).

Much research has been conducted on the public opinion on nuclear energy after the Fukushima accident (Kristiansen, Bonfadelli, & Kovic, 2018; Siegrist, Sütterlin, & Keller, 2014; Siegrist & Visschers, 2013). Most found that the accident only had a moderate effect on attitudes towards nuclear in Switzerland and mainly affected the perception of risk. This seems to be spatially differentiated—a 2016 analysis of over twelve thousand surveys in Switzerland found a statistically significant gradient of life satisfaction with the distance to nuclear power plants (Welsch & Biermann, 2016). Although correlation does not always mean causation, they find other correlations to support their hypothesis, such as lower gradients when the residents were shielded via wind direction or topography from the nuclear power plants.

To manage the nuclear phase-out without increasing carbon emissions, the Swiss government developed a policy roadmap called the *Energy Strategy 2050*. This Energy Strategy essentially contains the government's plans for the energy transition. Besides the nuclear phase-out, it aims to promote renewable energy and energy efficiency (SFOE, 2011).

In terms of energy efficiency and demand reduction, research shows that short-run electricity demand in Switzerland is highly price-inelastic, but becomes elastic in the long run (Filippini, 2011). Another study found that energy demand and GDP growth are significantly decoupled in Switzerland, implying that energy conservation policies would not hamper economic growth (Baranzini, Weber, Bareit, & Mathys, 2013). However, Moreau and Vuille (2018) find this can be explained by the embedded 'grey' energy in international trade that is normally not taken into account in national analyses. Regardless, Yuschenko and Patel create a model to assess the macro-economic impact of energy efficiency programs in Switzerland, showing positive GDP and employment benefits (Yushchenko & Patel, 2016, 2017). This is in line with Baranzini et al.'s findings and suggest well-targeted policies on energy efficiency could have significant benefits for Switzerland. However, Blumer, Mühlebach and Moser (2014) find that smaller Swiss utilities are not incentivized to work towards improving the energy efficiency of their clients. Considering that the Swiss electricity sector is highly fragmented with hundreds of relatively small urban utilities, this would imply large-scale energy efficiency improvements might be hard to achieve.

The renewable technologies to which the Energy Strategy 2050 attributes the most potential are wind, solar and hydropower. While natural gas is sometimes mentioned as a necessary bridging fuel, it is generally not envisioned by the government. Diaz, van Vliet and Patt (2017) find that gas is not necessary as a bridging fuel in Switzerland and would offer little to no cost savings. Dujardin et al. (2017) conclude that a fully renewable Switzerland is possible using just three technologies, finding that the scale and flexibility of Swiss hydropower adequately complements the intermittent production of wind and solar. Wind power is an important complement because, in Switzerland, it produces more electricity in winter than summer (Kruyt, Lehning, & Kahl, 2017), unlike solar and hydropower. However, wind power has not seen significant development in Switzerland because of strong public opposition and permitting delays (Walter, 2014). A study on the public opinion on wind energy in Switzerland found that aesthetics, performance, and economic feasibility were the three crucial determinants of the public's perception on wind power, but public participation in the planning process has proven effective to eliminating these barriers (Spiess, Lobsiger-Kägi, Carabias-Hütter, & Marcolla, 2015). In contrast, another study finds that Geneva in particular and Switzerland in general show a relatively positive outlook for the development of solar, especially on urban rooftops, as the building heights are relatively uniform and Swiss cities are not very compact (Mohajeri et al., 2016). With regards to hydropower, the domestic growth potential is limited with most of the suitable locations already being exploited (SFOE, 2012). An analysis by Gaudard (2015) further found showed that new pumped-storage facilities do not have a positive net present value (NPV) in Switzerland, although the present value from a real options perspective is substantial.

The Energy Strategy 2050 as a policy roadmap was planned to be implemented through multiple legislative packages, starting with a revision of the *Energy Law*[3]. The legislative process started in 2011, and after a successful referendum in 2017, the law entered into force in January 2018, confirming the gradual nuclear phase-out and promotion of renewables and efficiency into federal law (SFOE, 2017b). A revision of the *Electricity Supply Act*[4] was started in 2014; the legislative process has not yet finished as per October 2019. Part of the proposed revision is full market liberalization, bringing Switzerland closer to the EU in terms of market design, and a strategic energy reserve, to safeguard security of supply during the energy transition. The EU-Swiss relationship and the strategic energy reserve are the subject of the second and third studies of this thesis, found in Chapter 3 and Chapter 4, respectively.

Switzerland is strongly connected to and dependent on the EU electricity system for historical reasons and due to Switzerland's geographical position, but there is no Swiss-EU agreement on electricity. This continued lack of agreement has deteriorated trading conditions. By analyzing market data, Ciarreta and Zarranga (2015) show that market integration has halted between Switzerland and Germany, its largest trading partner. Further integration would be conditional on policy harmonization or an explicit agreement between Switzerland and the EU, which has been in negotiation since 2007. However, a 2014 immigration referendum in Switzerland chilled overall Swiss-EU relations, temporarily halting negotiations and making it less likely an electricity agreement will be reached in

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[3] *Loi sur l'énergie* (LEn) in French, *Energiegesetz* (EnG) in German.
[4] *Loi sur l'approvisionnement en électricité* (LApEl) in French, *Stromversorgungsgesetz* (StromVG) in German.

the near future. The impact of this evolving relationship with the EU on Swiss energy policy and governance is the subject of the second study (Chapter 3).

The Energy Strategy 2050 likely entails a growing dependency on electricity imports, which in combination with the political situation raised concerns in Switzerland about security of supply and the energy transition. Renewables, especially solar and hydropower, have a strong seasonal character, producing most of their electricity in summer, unlike nuclear power which can produce electricity year-round. Even if nuclear can be substituted fully by renewables on an equivalent annual production basis, winter imports will likely increase. This was shown by a multitude of scenario studies (Densing, Panos, & Hirschberg, 2016), including studies by the Swiss government and is confirmed also by this thesis in the first essay. The strategic energy reserve, part of the revised Electricity Supply Act, is meant to safeguard security of supply during the energy transition. Interestingly, Blumer et al. (2015) find that the concept of security of supply is viewed differently by the Swiss public, who link the concept to energy independence, and industry experts, who view it as the absence of supply disruptions. The strategic energy reserve is meant to aid in the latter, not the former. It incentivizes power plant operators with storage capabilities, which are mostly hydropower plants in Switzerland, to keep a minimum amount of energy in reserve, so that this energy can be called upon and converted into electricity in periods of scarcity. Strategic reserves have been implemented in electricity systems in other countries, but they have exclusively been strategic *capacity* reserves, not *energy* reserves. Since there is little experience from other countries to draw from about the policy's effectiveness, the strategic energy reserve is the topic of the third study in this thesis (Chapter 4).

1.2 Research philosophy

According to O'Gorman and Macintosh (2015), it is best practice for any researcher to define their *research paradigm* when writing down their study, so that others can understand the researcher's basis for claiming to know what she or he knows. A research paradigm is a broader concept than research methodology, although the latter is arguably a part or a logical consequence of the former. Harré (1987, p. 3) defines a research paradigm as "a combination of a metaphysical theory about the nature of the objects in a certain field of interest and a consequential method which is tailor-made to acquire knowledge of those objects". The definition offered by Harré can be divided into two parts. The first part essentially points to a *research philosophy*, commonly understood to be defined by the researcher's epistemological, ontological, and theoretical perspective. The second part, then, is the methodology, which should follow from or correspond to the research philosophy. This section describes the research philosophy underlying this thesis and informing the methodologies chosen in the next chapters to analyze each energy policy issue.

The first aspect of research philosophy is ontology, commonly described as one's thinking about the "nature of existence" (e.g. O'Gorman & MacIntosh, 2015, p. 55). Broadly speaking, ontologies exist on a continuum between two opposites: an objective and a subjective ontology. Other researchers might refer to the same continuum with different names, such as realist and relativist (e.g. Gray, 2004; Moon & Blackman, 2014) but their meaning remain largely identical. An objective or realist ontology ascertains that there is a single, objective reality out there, independent from the human mind. Objects have certain observable properties and the world works in certain ways, which are independent of the researcher. In contrast, a subjective or relativist ontology tells us that perceptions are what shape reality, and reality is thus subjective or relative to the individual. Observable properties and facts exist but are located and defined relative to the vocabulary and cultural historical context of the researcher. Most of the research in the natural sciences prescribes to an objective ontology, and most of the research in the social sciences leans towards a subjective ontology. However, subjective and objective ontologies are not necessarily mutually exclusive.

The second aspect of research philosophy is epistemology. If ontology describes the nature of reality, epistemology describes the nature of knowledge about that reality and how knowledge is obtained from it. The notions of epistemology and ontology are closely related but conceptually different. A definition of ontology is offered by Guba and Lincoln (1989, p. 108): “the nature of the relationship between the knower or would-be knower and what can be known”. Many types of epistemology exist. O’Gorman and MacIntosh (2015) differentiate between four: positivism, interpretivism, critical realism, and action research. Crotty (1998) identifies three: objectivism, subjectivism, and constructionism. The categorizations of Guba and Lincoln and Crotty follow a similar logic but are not identical. For instance, Crotty’s nomenclature resembles the ontologies described above because Crotty argues the distinction between ontology and epistemology is not important for most researchers.

Positivism and o*bjectivism* are similar and follow from a purely objective ontology: research is aimed at identifying the objective properties or truths about their research object. Knowledge and meaning are thus intrinsic in the objective reality, to be “discovered” by the researcher. *Interpretivism* is often considered the opposite of positivism and follows from a purely subjective ontology. Knowledge exists only in the human mind and the interpretations of the researcher and is therefore not intrinsic to the research object. It is usually followed in social sciences, where interpretivists assert that human observations (interpretations) of human behavior can never be objective and different realities exist in the minds of different individuals. *Critical realism* is related to positivism but falls somewhere in between a subjective and objective ontology. While it assumes that an objective reality exists, it is critical about our ability to access this objective reality. It states that all knowledge generated about the objective reality is based on the perception of the observer and therefore all knowledge is subjective, even if reality is objective. This is closely related (although not identical) to Crotty’s *constructionism*, which states that meaning and knowledge do not come from the objects themselves inherently but are constructed by interaction with the object and will therefore depend on the researcher’s subjective perception. *Subjectivism*, in contrast to constructionism, follows the logic that meaning is imposed on the object and generated ‘out of nothing’, rather than constructed through interaction with the object. The last epistemology that O’Gorman and MacIntosh identify, *action research*, is considered by many as a methodology (or a category of methodologies) rather than an epistemology. However, according to O’Gorman and MacIntosh (2015), it should be classified as an epistemology on its own. Action research continues from the assumption that knowledge is always grounded in a local, subjective, temporary reality, and that knowledge should therefore be applied on the research object actively during the generation of it—a type of ‘learning by doing’, so to say, focusing on solving real-world problems.

The last element of a research philosophy is one’s theoretical perspective on research, which ultimately is supposed to bridge the gap between ontology and epistemology on the one hand, and research methodology on the other. Crotty defines it as “the philosophical stance informing the methodology and thus providing a context for the process and grounding its logic and criteria” (1998, p. 11). It describes the assumptions underlying the choice and the justification for the choice of methodology. Moon and Blackman (2014) group theoretical perspectives by the intent of the researcher, rather than describing specific theoretical perspectives in detail, which is a particularly useful approach in narrowing down a research philosophy. They identify five categories of intent: to predict, to understand, to emancipate or liberate (change), to deconstruct, and “any and all”. Most of these category names are self-evident, except perhaps the last. In that category, Moon and Blackman place only *pragmatism*, a theoretical perspective that says research should be “contextually situated without being committed to any one philosophical position, instead using a diversity of methods to understand a given problem” (2014, p. 1175). A pragmatic theoretical perspective thus starts from a problem and places more emphasis on usefulness and practical consequences, and less on a specific research philosophy.

My ontology is neither fully objective nor subjective, but I lean towards a **subjective ontology**. Having a background in theoretical physics, I have learned even the most objective reality is relative to the observer. Quantum physics describes how one thing can be simultaneously true and not true at the same time; how a single particle can be in more than one location at the same time. Einstein’s relativity theory describes how observable properties like speed, distance or time are relative to the observer’s frame of reference. However, these theories still describe fundamentals of reality and all of reality should objectively abide by them. The policies that I analyze and the models that I create in this thesis are shaped by my own perceptions of reality. Furthermore, the research object, which in my case is the impact of these policies, lies in the future. As the future is inherently unknowable and uncertain, there can be no true or objective reality that my research aims to observe. The impact of future policies is impacted by our own perceptions of them and embedded in our contemporary cultural context. The study of the policy itself could change the impact of policy, by changing policymakers’ perceptions about the policy. My research can therefore not truly be interpreted as true or false, suggesting only a single objective truth exists, but should instead be judged by its degree of usefulness to society now.

Coming from a mostly subjective ontology, my research can be seen as following a **constructionist epistemology**. In such an epistemology, knowledge is constructed by our interaction with reality. A simulation model is my version of a constructed reality, based on my experience and knowledge of reality. The meaning of the generated knowledge comes from interaction with the world and serves as a new object for readers to construct knowledge in their own mind, contributing to their world view. Their perceptions and their constructed knowledge can change their behavior and ultimately even shape or change the policy.

Lastly, my research follows a **pragmatic theoretical perspective**. The policies in my research and the research questions that I pose around them are all shaped by a contemporary problem which require informed decisions by practitioners. The value and meaning of my research, then, is thus mostly derived by the usefulness of the study in solving the problem and not necessarily the research philosophy. Although the contributions of this thesis extend beyond the contextually situated practical implications, the common research philosophy of the nascent field of sustainability transitions also works from this narrative—find solutions to contemporary and future sustainability problems.

Chapter 2 Timing the nuclear phase-out

This chapter contains the first essay of this thesis and is based on the post-print of the following article:

> van Baal, P., Verhoog, R., & Finger, M. (2017). Not if, but when? Simulating the impact of timing the nuclear phase-out in Switzerland. *Conference Proceedings of the International Symposium for Next Generation Infrastructure, London, September 13-15, 2017* (pp. 425-434). Available from http://isngi.org/wp-content/uploads/2017/10/ISNGI-Conference-Proceedings-v2.pdf

An abstract of the article was originally submitted on May 21st, 2017 and accepted for participation in the conference on June 9th, 2017. The full article was submitted on July 16th, 2017. A revised version after peer review was submitted on August 24th, 2017, accepted on September 3rd, 2017 and published online on December 20th, 2017. Although the study was a collaborative effort with all three authors, my personal contributions were substantial: creating the research design, creation of the conceptual and formal model, performing the simulations, analyzing the results, and writing the article.

2.1 Abstract

Swiss electricity companies are faced with uncertainty with regards to the future operation of nuclear power plants in the country. After the Fukushima disaster in 2011, the government decided on a gradual phase-out, but only provided a tentative planning. Hence, no new nuclear power plants can be constructed but the old power plants will be allowed to operate until they are no longer deemed safe by the nuclear regulator ENSI. However, the first of the five Swiss nuclear reactors will shut down in 2019, following a decision of the owner, not ENSI, three years ahead of the government's original schedule. Recent efforts by politicians and citizens to fix the date of the phase-out were unsuccessful. In this paper, we look at the effect of the timing of the phase-out and the associated uncertainty on the wider electricity market. More specifically, we look at the impact on investments, security of supply, wholesale electricity prices, and the amount of greenhouse gas emissions. We developed a simulation model using system dynamics to increase our understanding of the Swiss nuclear phase-out. The system dynamics model includes modules for merit order dispatch, international trading, investment analysis, generation capacity expansion, hydropower storage and dispatch, and other renewable electricity production. The model is based on data of the Swiss electricity system and includes anticipated policy changes of the wider energy transition in Switzerland. The simulations are based on various scenarios of both timed and untimed nuclear phase-outs with varying levels of uncertainty and show that the timing uncertainty does not significantly impact market development. Investors seem to wait for observable rather than anticipated market changes. However, delaying the nuclear phase-out does have significant advantages in terms of greenhouse gas emissions and security of supply. The implications of these findings are discussed in the context of the Swiss Energy Strategy 2050 and the country's obligations under the Paris Agreement.

Keywords: electricity market; investment; security; energy transition; system dynamics; simulation; Switzerland; nuclear phase-out; uncertainty

2.2 Introduction

Switzerland has committed to a challenging transformation of its electricity supply infrastructure. The alpine federation is currently relying on domestic nuclear power for slightly over a third of its electricity supply, the remaining two thirds supplied by hydropower and a small fraction by waste incineration and new renewables such as wind and solar (SFOE, 2016). After the Fukushima accident in 2011, Switzerland decided to cease granting permits for new nuclear power plants, effecting a gradual nuclear phase-out in the near future as Switzerland's five nuclear reactors are the oldest nuclear power plants in the world (World Nuclear Association, 2017). This decision was recently reaffirmed by a popular vote that simultaneously pushed forward the development of new renewables and energy efficiency as the solution to the future gap in power supply (SFOE, 2017a). However, the development of alternative supply in the form of new renewables is facing many problems in Switzerland: social acceptance (Wüstenhagen, Wolsink, & Bürer, 2007), low potential (SFOE, 2012), low economic attractiveness (Prognos AG, 2012), and a high policy risk (Karneyeva & Wüstenhagen, 2017), all possibly leading to investor reluctance. Electricity imports can provide temporary relief. However, Switzerland's overall objective is to remain relatively self-providing and the cross-border transmission capacity is already showing signs of congestion due to Switzerland's central location for inter-European trading (Schlecht & Weigt, 2014). Expansion of domestic fossil fuel power plants such as natural gas would likely result in large public opposition as well as potential conflicts with the Swiss climate ambitions and obligations under the Paris Accord, aiming to reduce greenhouse gas emissions by 50% by 2050 (Jorio, 2017).

It is clear that the decision to phase out nuclear energy brings a large amount of uncertainty to the forefront of an electricity industry already facing numerous other challenges. Although the country is committed to the phase-out, it is not bound by a schedule. A recent popular vote to limit the lifetime of the existing nuclear power plants to 45 years and effectively provide a schedule was rejected (BBC, 2016). The fleet of power plants was originally built to last 30 years, but the expectation is that they will manage to be safely operated for 50 years or longer. Power plants and other electricity infrastructure take several years to construct (Schwarz, Grünenfelder, von Metzler, Cox, & Turner, 2012). Without a schedule, the market is given little prior warning, making it hard to build a replacement source of electricity supply in time after the decision has been made to shut down a reactor. Temporary supply shortages can lead to price spikes, system instability, and other security of supply issues.

A model of the Swiss electricity system based on system dynamics was made to explore the impact of this uncertainty on the electricity system and Swiss obligations under the Paris Agreement. Specifically, we look at the length of the notice period for each nuclear reactor's shutdown and the impact on investments, security of supply, wholesale electricity prices and the amount of greenhouse gas emissions. The results will indicate whether providing more clarity to the market players will be overall beneficial.

2.3 Methodology

Long-term energy system models can be broadly categorized into three groups: equilibrium models, optimization models, and simulation models (Ventosa, Baíllo, Ramos, & Rivier, 2005). Equilibrium models assume that rational actors interact under rules of perfect competition in such a way that equilibrium prices are reached. An electricity system in transition entails significant system delays and actors have imperfect information and is thus clearly out of equilibrium, as many researchers have shown (Gary & Larsen, 2000; Hasani & Hosseini, 2011; Olsina, Garcés, & Haubrich, 2006).

Optimization models assume perfect foresight and a single, omniscient planner to direct the evolution of the system based on cost minimization or some other optimization criteria. Even the most sophisticated constrained optimization models do not forego that basic assumption, which makes them unsuited to explore the question of bounded rationality, imperfect competition and time delays in this study.

Simulation models, which include a range of options including bottom-up approaches such as agent-based modeling and top-down approaches like system dynamics, are better suited to model electricity markets under these conditions (Teufel, Miller, Genoese, & Fichtner, 2013). We chose system dynamics because we are concerned with system-level impacts of the uncertainty surrounding the nuclear phase-out. System dynamics can adequately deal with long-term feedback, time delays, bounded rationality, and imperfect information (Teufel et al., 2013), necessary for adequately exploring our research topic.

2.3.1 Model description

The model was created on the Vensim® DSS for Windows 6.4E software platform. It is an extension of earlier work at EPFL (van Baal, 2016; Verhoog, van Baal, & Finger, 2018). The additions made to the model for this study include carbon dioxide emissions, a variable notice of each reactor's planned shutdown ("*investor foresight*") and additional phase-out schedules. A brief introduction to the model follows below. An overview of the conceptual model and the full set of model equations are included as appendices to this thesis—Appendix A (p. 125) and B (p. 128), respectively.

The model simulates the Swiss electricity system between 2015 and 2050, aligning with the Energy Strategy 2050 and allowing sufficient time to explore long-term problems. The model has an hourly resolution, unlike other models of the Swiss market which have used months or representative days in order to cut back on simulation time (Ochoa & van Ackere, 2009; Osorio & van Ackere, 2016). An hourly resolution is necessary to explore system instability and price spikes, as these are not expected to happen on representative or average days but rather on those exceptional days when multiple factors concur, e.g. unfortunate weather, maintenance schedules, network congestion, or high demand. This next part will qualitatively describe the way the model functions.

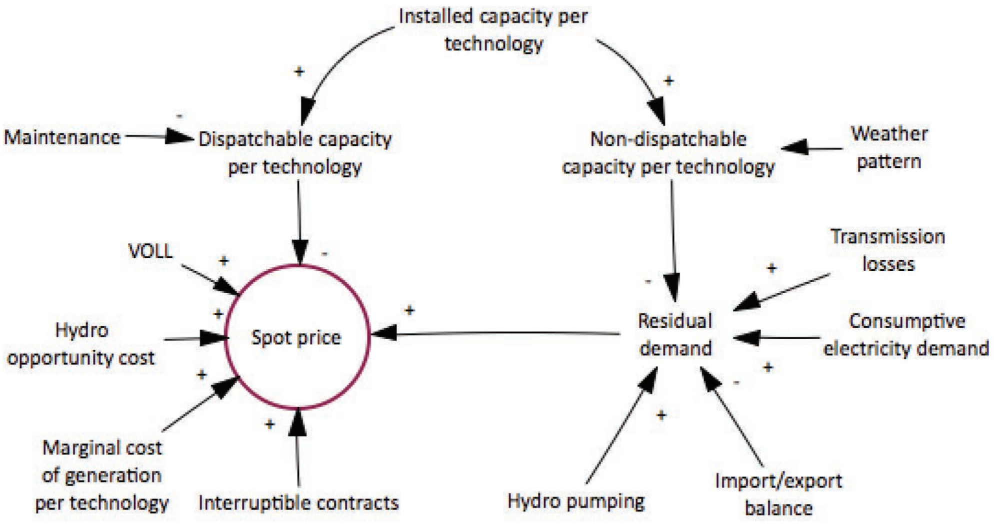

Figure 2.1: Conceptual overview of the spot market and merit order dispatch.

The model centers on the spot market and merit order dispatch (Figure 2.1), but also includes other important factors such as international trading, investment analysis, generation capacity expansion, hydropower storage and dispatch, and other renewable electricity production. Merit order dispatch is based on marginal costs of the generation technologies (de Vries & Heijnen, 2008; Osorio & van Ackere, 2016; Schwarz et al., 2012). The exception is hydropower, both pumped storage and regular, of which the bidding prices are based on opportunity costs, reflecting the ability of operators to plan the use of their resources strategically (Densing, 2013). Opportunity costs are inversely related to the availability of water, scaling in relation to the market prices and marginal prices of alternatives in a similar fashion as other studies (Osorio & van Ackere, 2016; Vogstad, Botterud, Maribu, & Jensen, 2002). Hydropower pumped storage and international trading are performed in a similar fashion, comparing spot prices with available capacity[5] and trading or pumping whenever deemed profitable. These transactions happen ex-ante, i.e. before the market is cleared, thus reducing the residual demand. A part of the international trade is also done via long-term bilateral contracts, notably fixed-price call options with France (VSE, 2012). These function in the merit order in the same way as domestic dispatchable power but also reduce the available NTC for spot trading with France when utilized.

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[5] Pumping availability is based on actual reservoir modeling. Hourly Net Transfer Capacities (NTC) for each neighboring country is calculated using future projections of annual maxima (ENTSO-E, 2014) and historical data for hourly patterns (ENTSO-E, n.d.).

The model uses several exogenous inputs. Foreign spot prices are taken as exogenous and modeled using 2010-2014 data to generate hourly profiles (EPEX Spot, n.d.; GME, n.d.), combined with future projections from the European Network of Transmission System Operators for Electricity (ENTSO-E, 2014). Consumptive demand growth is implemented using projections taken from the VSE, the Swiss Association of Electricity Producers (Schwarz et al., 2012), coupled with standardized hourly profiles generated from historical data (Swissgrid, n.d.). This means the model does not explicitly take into account possible changes to demand patterns due to e.g. electric vehicle charging or price elasticity (Filippini, 2011). Weather patterns are similarly created from historical data and future projections and impact weather-dependent parts of the model such as run-of-river and reservoir inflow (Schwarz et al., 2012; SFOE, n.d.), wind (Kunz et al., 2004; NOAA, n.d.), and solar (Huld, Müller, & Gambardella, 2012).

The model also includes a module for investment analysis and project development (Figure 2.2). The project pipeline traces each project from permit application through approval, construction, operation and decommissioning and is based on the work of Vogstad et al. (2002). There are two decision points for investors based on the investment analysis. The first is at the permit application stage. After the permit has been approved, the project comes into a stock of approved projects and will only start construction after an investor decides to go forward with the project. If this takes too long, the building permit can also expire.

Investment analysis is done by estimating a project's internal rate of return (IRR) and comparing it to a corporate hurdle rate (Schwarz et al., 2012). This is a proven way to model investor behavior which many other researchers have taken in similar works as well (Bunn & Larsen, 1992; Hasani & Hosseini, 2011; Olsina et al., 2006; Pereira & Saraiva, 2010). Inputs for IRR calculation are plagued by bounded rationality—investors do not have perfect foresight and base their decision on the information available to them and their expectations on the future state of the system. Investors are made aware of each nuclear reactor's shutdown one to six years in advance, allowing them to plan accordingly. Since the delays associated with building power plants range between one to four years depending on the technology (Schwarz et al., 2012), this may or may not be enough time to build sufficient new generation capacity. The decommissioning of Mühleberg, which is the first reactor to shut down, planned for 2019, was announced 3 years in advance by the operator due to economic reasons (World Nuclear News, 2016), and not by the nuclear regulator ENSI due to safety concerns. Should the ENSI detect safety concerns and force the reactor to shut down, the notice would likely be shorter than 3 years.

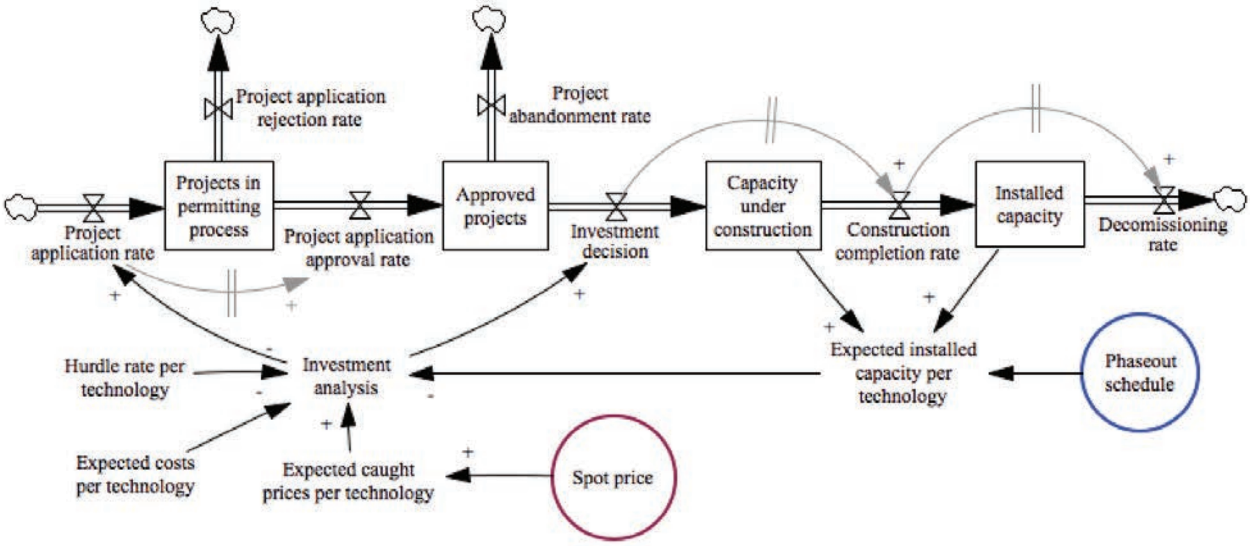

Figure 2.2: Conceptual overview of investment analysis and project development.

Endogenous investments are made for solar power, wind power, and combined cycle natural gas turbines (CCGT) using cost structures including carbon prices and learning curves from the VSE (Schwarz et al., 2012) and subsidy schemes as currently in place and planned in Switzerland. Investments in other power generation options, notably hydropower, are taken as exogenous (Schwarz et al., 2012). This is done because other investments options are prohibited (i.e. nuclear), marginal (e.g. geothermal), or already exploited to their maximum potential (e.g. hydropower, waste-to-energy), and their respective impacts are therefore strongly limited. Investors only incorporate the projects that are under construction in their investment decisions and no permit applications or approved projects by other investors as these are not definitive yet.

2.4 Results

The next section will discuss the results. The model contains over 600 variables and numerous different possible scenario combinations. We discuss the results that are most relevant to the Swiss energy transition, focusing on the uncertainty surrounding the nuclear phase-out. Most findings will be supported by visual evidence, but some findings will only be discussed in-text.

The first insight from Figure 2.3 is that the Swiss electricity price will most likely remain at or around 50 CHF/MWh, for at least the coming 10 years. Averaged over the coming half-century, we can observe a slow positive trend in the electricity price. Although the uncertainty grows exponentially in electricity price forecasting, we find that nearing 2050, the electricity price will most likely be in the range of 50-90 CHF/MWh. However, the price development is strongly dependent upon domestic demand developments (Figure 2.4). The simulation uses three different demand scenarios, taken from the VSE (Schwarz et al., 2012). The first scenario sees electricity demand grow, stabilize, and then decline. In the second, demand simply stabilizes and in the final scenario demand keeps growing (although at an increasingly smaller rate). The electricity price in the growing demand scenario is roughly a third higher than in the declining demand scenario (Figure 2.4). It cannot be said with high certainty how electricity demand will develop. There are strong domestic, and global, efforts to reduce consumption and increase efficiency on the one hand, but on the other hand, further electrification of energy services is anticipated as well. A medium or growing demand scenario seems more likely in light of the Energy Strategy 2050, which both stimulates electrification of heating and mobility, as well as an increase in energy efficiency.

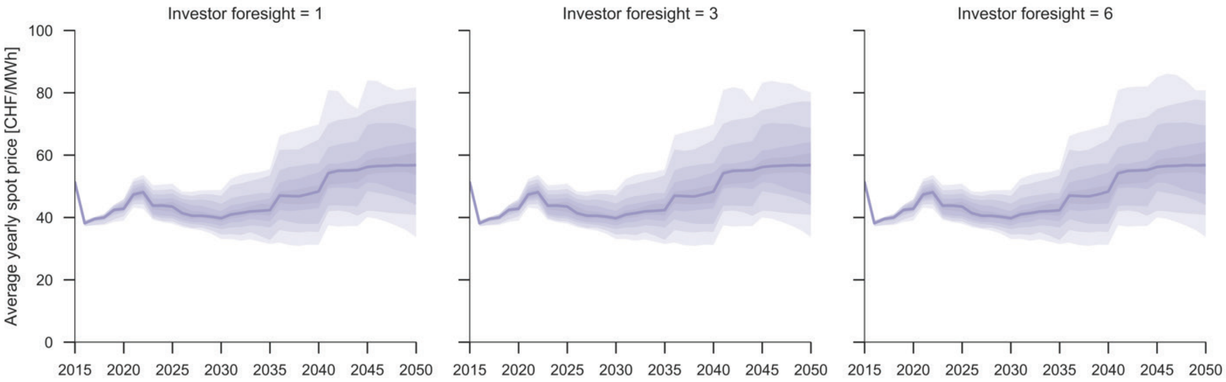

Figure 2.3: Yearly average spot price when investors are given 1 (left), 3 (middle), and 6 (right) years of notice.

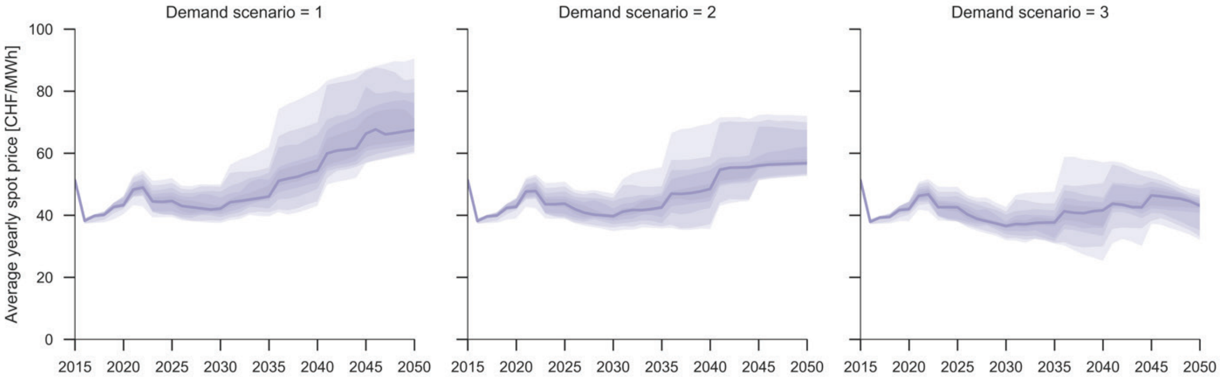

Figure 2.4: Yearly average spot price in simulations with growing (left), stabilizing (middle), and declining (right) demand.

The second impact from timing the nuclear phase-out could be that investors change their investment behavior to anticipate the decommissioning of the nuclear power plants. However, we find no substantial differences in investments behavior. If we isolate the scenarios where demand keeps growing the coming decades, some CCGT power plants are built and we observe a slightly more differentiated pattern than in Figure 2.3. However, the differences remain negligible. From this we can conclude that timing the nuclear phase-out earlier in advance will probably not impact the electricity market development, and little risk is posed by allowing the owners and nuclear regulator ENSI decide each shutdown ad hoc.

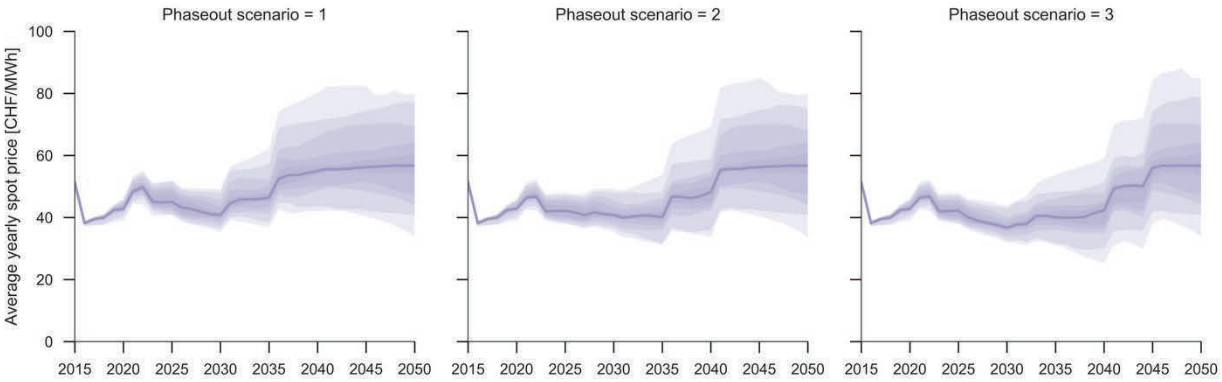

Figure 2.5: Yearly average spot price when nuclear power plants have an average 50 (left), 55 (middle), and 60 (right) years of lifetime.

However, another factor remains, and that is the average lifetime of each nuclear power plant. In Figure 2.5, we find that an eventual electricity price increase is postponed in those instances where the lifetime of the nuclear power plants is extended further than the 50 years originally anticipated in 2011 by the government (SFOE, 2011). This is not unexpected, as less investments have to be made and the marginal costs of operating nuclear power plants are relatively low compared to other generation options. The figure suggests that the electricity market will develop differently depending on the eventual nuclear phase-out path. What is most relevant to see is whether this change will have an impact on security of supply and on the eventual amount of greenhouse gas emissions.

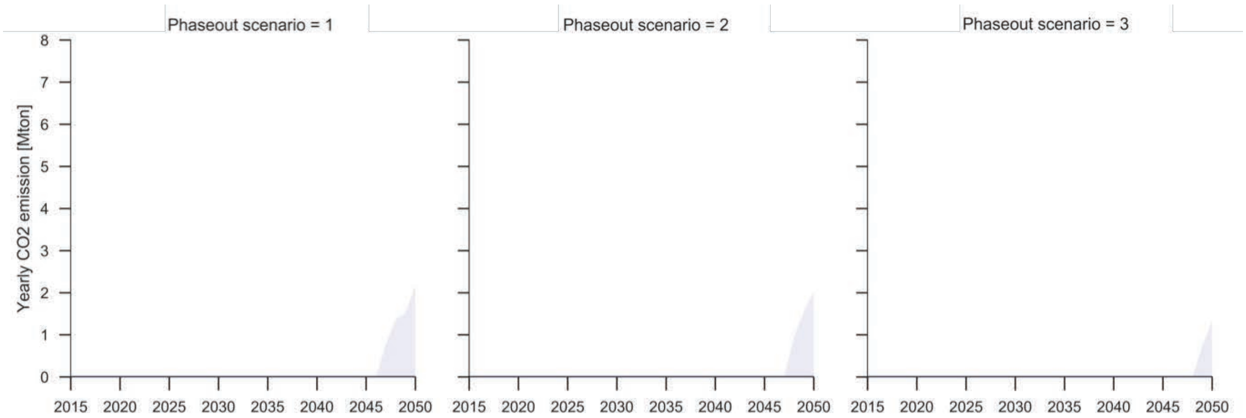

Figure 2.6: Additive yearly CO_2 emissions compared to 2015 with a growing NTC capacity and when nuclear power plants have an average 50 (left), 55 (middle), and 60 (right) years of lifetime.

Looking at additive power-related CO_2 emissions[6] in Figure 2.6, we find that emissions are likely mildly lower by the end of the half-century if the phase-out is delayed. We postulate two logical reasons for this. Firstly, the fact that lower average electricity prices persist makes it harder for CCGT to compete. Secondly, and perhaps more intuitive, is that the possible supply gap due to the phase-out is postponed and it is harder for CCGT power plants

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[6] "Additive emissions" means the emissions related to newly built power plants only.

to compete in the future, where solar and wind are expected to be more competitive than they currently are due to learning effects and cost reductions.

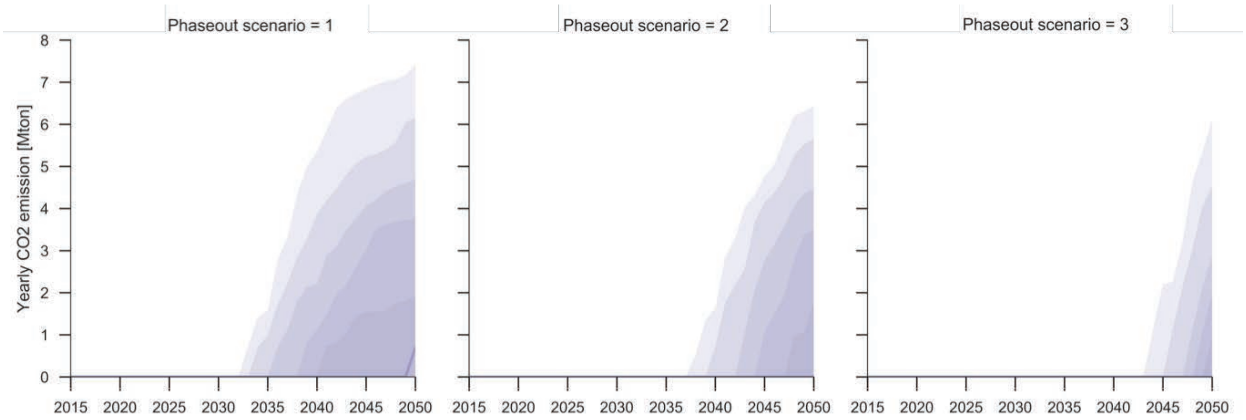

Figure 2.7: Additive yearly CO_2 emissions compared to 2015 with a constant NTC capacity and when nuclear power plants have an average 50 (left), 55 (middle), and 60 (right) years of lifetime.

However, this difference becomes significantly more pronounced when plotting the same figures while not allowing for cross-border trading capacity to expand following the ENTSO-E Ten Year Network Development Plan (ENTSO-E, 2014), as we assumed in all previous graphs, but rather keeping them at their current value (Figure 2.7). Investments into CCGT are then strictly necessary as there is not enough availability to import electricity. Greenhouse gas emissions grow significantly, potentially reaching heights of up to 7 MT CO_2 per year, approximately 13% of the Kyoto 1990 baseline for Switzerland (BAFU, 2014). In essence, this is what will be necessary if Switzerland does not want to expand its import dependency and keep their electricity supply locally generated. We find this effect to be the strongest when domestic electricity demand is growing, mild when demand growth stabilizes, and disappearing altogether when demand can be reduced from today's situation. This shows the importance of curbing electricity demand growth. Simultaneously it shows the inherent risk entailed by aggressively electrifying heating and mobility services, namely that it will merely shift emissions to the power generation sector.

Greenhouse gas emissions are not the only important indicator of the market development. Security of supply is crucial too. Power shortages, even if they last relatively short, pose a high risk to the Swiss economy, potentially causing billions in damages (BABS, 2015). Figure 2.8 illustrates the development of the security of supply. Note the change of axis with respect to the previous figures. A spike in electricity price signal scarcity and a high risk for blackouts. The risk completely disappears when demand is declining (right). The risk also completely disappears when the NTC is assumed to develop according to the ENTSO-E plan, as seen in Figure 2.3 and Figure 2.5.

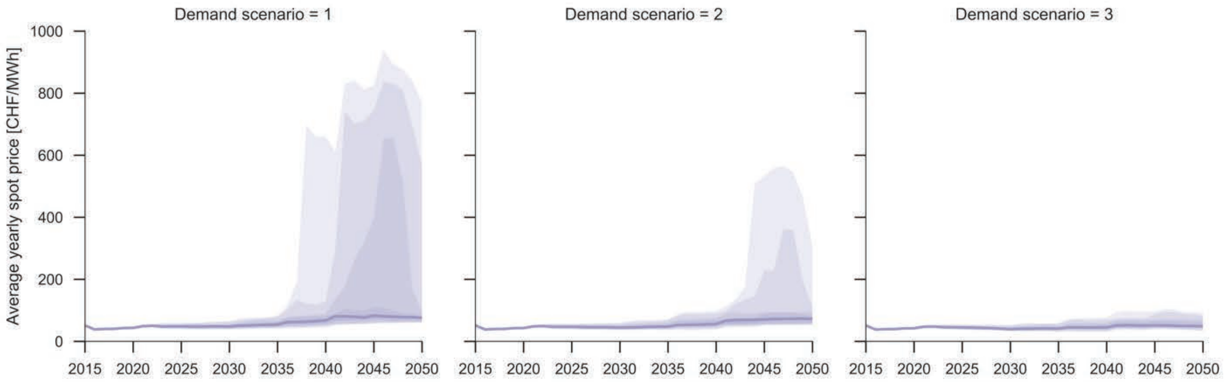

Figure 2.8: Yearly average spot prices in simulations with a constant NTC capacity and growing (left), stabilizing (middle), and declining (right) demand.

2.5 Discussion and conclusion

Switzerland decided to phase-out nuclear energy in 2011 after the nuclear fallout in Fukushima and reaffirmed this position by popular vote in 2017. The chosen phase-out pathway is marked by high levels of uncertainty for investors and potential risks to the security of supply as nuclear is currently an integral part of its supply. Swiss commitments to reduce carbon emission under the Paris Accord further complicate the transition. Unique for the case of Switzerland is the already low amount of carbon emissions associated with electricity production, as most power in the country is supplied by a combination of nuclear and hydropower. Switzerland does not currently have any fossil fuel power generation, meaning most emission reductions will have to come from other sectors such as mobility and heating, undoubtedly necessitating a further electrification for both.

To investigate these matters, we developed a system dynamics model of the Swiss electricity system, including the spot market based on an hourly merit order, new investments in CCGT, wind, and solar, international trading, and hydropower reservoirs and strategic bidding. We used this model to investigate the impact of the uncertainty surrounding the phase-out on Swiss electricity prices, power generation investments, greenhouse gas emissions, and security of supply. The model estimates the CO_2 emissions per year from newly built CCGT plants, and thus represents the additional burden of CO_2 reductions that Switzerland will have to capture, offset or reduce in other parts of their economy in order to meet their emission reduction targets.

Our simulations showed that timing the nuclear phase-out further in advance does not significantly impact the market development. Investors seem to wait for actual market changes rather than anticipated changes. Thus, we identify no inherent risk to allowing the nuclear regulator ENSI decide each reactor's decommissioning on an ad-hoc basis. However, the lifetime of the nuclear power plants was found to be more important. We can clearly see that the chosen phase-out pathway in Switzerland, where the nuclear power plants are allowed to operate for an undetermined time period but cannot be replaced, has both upsides and downsides. Nuclear provides stability in the Swiss electricity market for now, which is hard to replace solely by renewables such as solar and wind. A strong dependency on imports will be the most likely result, which will mean a lower security of supply in Switzerland overall. If demand growth can be curbed, this trade-off will be smaller and the transition objectives in the Paris Accord and the Energy Strategy 2050 will be more easily and securely met.

Our results further show a clear trade-off between increasing the dependence on electricity imports and the domestic development of natural gas-fired power plants in order to keep the security of supply sufficiently high. If the nuclear phase-out is delayed, or if demand growth can be significantly curbed with respect to today's levels, this trade-off becomes less strong. Under current UNFCCC[7] rules, the carbon emissions from imported electricity do not count as domestic emissions, and hence it would be easier for Switzerland to meet its greenhouse gas reduction targets by increasing their cross-border trading capacity rather than domestic generation. We found that the amounts of greenhouse gas emissions from newly built CCGT power plants can reach heights of 7 million tons per year, about 13% of the 1990 Kyoto baseline for Switzerland (BAFU, 2014). This would mean a huge amount of emissions need to be captured or elsewhere abated to reach the climate goal of 50% fewer emissions in comparison to this baseline. However, domestic power plants are a more reliable supply option than electricity imports, where cross-border congestion can mean supply issues for Switzerland if the dependence becomes too high. Several simulations have shown power shortages as a result of an excessive dependence on imports in winter. Further research will have to be done to assess the security of supply risks associated with the Swiss energy transition.

We identify a few limitations to our analysis. First, the system boundaries are set such that only domestic affairs are modeled endogenously. The assumption is that the electricity markets in the much larger neighboring countries France, Italy, and Germany will not be influenced significantly by the developments within Switzerland. Investments in cross-border transmission capacity are similarly exogenous, which can have an impact on the findings given the importance of imports and cross-border congestion to the security of supply in certain scenarios. Second, we use standardized hourly demand profiles, meaning that the seasonal and hourly load distribution is kept constant throughout the simulation. Any impact the electrification of services will have on the relative timing of the demand peak, e.g. with regard to the seasons or daily solar pattern, is not included. This can have an influence on the viability of hydropower, storage, and solar technologies, as well as the market evolution in general. Third, system dynamics aggregates all power plants of each technology into a single stock, meaning there are no individual constraints or differentiated costs for individual power plants. Fourth, the entire market is represented by the spot market, meaning the other electricity markets and supply contracts are not explicitly modeled. The spot market is generally the most volatile, and this can be reflected in the results. Lastly, it has proven incredibly difficult to predict the developments of the costs of renewables in the long term. The investment behavior and electricity market might change substantially if the developments differ from the projections used in this model.

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[7] United Nations Framework Convention on Climate Change.

Chapter 3 Swiss-EU relations in energy

This chapter contains the second essay of this thesis, and is based on the post-print version of the following article:

van Baal, P. A., & Finger, M. (2019). The Effect of European Integration on Swiss Energy Policy and Governance. *Policy and Governance, 7*(1), 6-16. doi:10.17645/pag.v7i1.1780

The article was originally submitted on October 12th, 2018. After a round of peer review, the article was revised and resubmitted on December 4th, 2018, and finally accepted for publication on December 6th, 2018. The article was published online on March 28th, 2019. Although the research was a collaborative effort, my personal contribution to the study was substantial: creating the research design, creating the interview format, performing most of the interviews, analyzing the documents and interview data, the theoretical analysis of the results, and writing the article.

3.1 Abstract

The unique "Swiss way" of association with the European Union has received increasing attention in light of recent events such as Brexit as it is based on sectoral agreements without an overarching institutional framework. As such, Europeanization of Swiss domestic policy does not follow a straightforward process. We examine the external governance processes that drive the Europeanization of Swiss energy policy. Switzerland and the EU are highly interdependent in matters of electricity due to Switzerland's geographical position but there is a relatively low level of policy alignment, as there is no formal EU-Swiss energy agreement nor has Switzerland autonomously implemented legislation equivalent to the EU energy acquis. The EU has fully liberalized the energy market and is focusing on consumer empowerment and decarbonization through the Clean Energy Package, whereas the Swiss energy sector remains only partially liberalized. Through a series of expert interviews with key stakeholders, we reconstruct the historical developments in Swiss energy policy, focusing on the relationship with, and the influence of the EU. We observe elements of each of the three ideal modes of governance—markets, hierarchies, and networks. The relative importance of these modes of coordination in governing EU-Swiss energy relations has shifted considerably over time. Gradual harmonization of EU energy markets and certain key events have driven Swiss exclusion from EU network governance processes, leading to more hierarchy. We identify the strengths and weaknesses of each mode of governance for EU-Swiss energy relations in their historical setting and discuss the implications for energy policy in Switzerland in the context of the Clean Energy Package and EU external relations in general.

Keywords: energy policy; European Union; external governance; history; network governance; power; Switzerland

3.2 Introduction

The European Union associates with third countries in a variety of manners (Lavenex, Lehmkuhl, & Wichmann, 2009). The unique “Swiss way” of association has received increasing attention in the context of Brexit because Switzerland has no institutional framework agreement with the EU (Tobler, 2016). The EU-Swiss relationship is defined by sectoral agreements. Additionally, Switzerland has significantly aligned its domestic legislation with the EU in certain sectors without a formal agreement. There have been various quantitative studies on the influence of EU policy on Swiss policy (Bartle, 2006; Gava & Varone, 2014; Jenni, 2015). However, few analyze the governance processes that drive such adaptation. Identifying these processes is important because the absence of an institutional agreement between the EU and Switzerland implies a lack of standard procedures of association and could provide insight into future relations between the EU and other countries.

The case of electricity is particularly pertinent as the reliable operation of an electricity system requires the continuous cooperation of all parties involved. However, there is no formal EU-Swiss agreement on electricity. European energy affairs have traditionally been coordinated through various private and public networks (Jegen, 2009), yet, Switzerland’s position in these networks has significantly deteriorated the last few decades, up to the point of exclusion in certain instances (Jenni, 2015). At the same time, Switzerland has committed to an ambitious energy transition focusing on the gradual phasing-out of nuclear energy, the most important source of electricity besides hydropower, which will likely increase its future dependence on the EU electricity system (Demiray et al., 2018; ElCom, 2018; Verhoog et al., 2018).

Research on policy diffusion tells us that uncoordinated, unilateral adoption of EU-compatible policies in Switzerland can result from either competitive or coercive pressure, or through learning and emulation (Börzel & Risse, 2012; Elkins & Simmons, 2005; Simmons, Dobbin, & Garrett, 2006). The EU external governance literature started from the observation that the EU sphere of influence extends beyond its Member States (Friis & Murphy, 1999) and has proven successful in explaining Europeanization processes (Lavenex, 2004; Mugyenzi, 2015; Schimmelfennig & Sedelmeier, 2004). Both policy diffusion and external governance use ‘conditionality’ as a key mechanism driving policy proliferation in third countries. However, unlike policy diffusion, external governance theory is not limited to the implementation of policies but includes other forms of coordination as well, often studying these in light of the traditional ‘modes’ of governance—markets, hierarchy, and networks (see, e.g., Knill & Tosun, 2009). Joint operation of the European power system requires continuous coordination between all countries involved, and external governance theory allows us to analyze all the governance processes involved. We use the external governance theoretical framework which was originally defined by Lavenex and Schimmelfennig (2009) to analyze the processes that drive the Europeanization of Swiss energy policy. The framework was developed specifically in a European context and offers several explanatory hypotheses regarding power relations, domestic structures, and EU institutions. As EU external governance modes are strongly path- and sector-dependent (Lavenex et al., 2009), we have to look at how the current situation has developed to discuss the future implications for European integration.

We, therefore, reconstruct the history of EU-Swiss energy governance by utilizing public reports, press releases and official government publications, alongside thirteen interviews with key stakeholders. All of the stakeholders interviewed were directly involved with EU-Swiss (energy) affairs at a certain point in the history. We interviewed seven high-ranking public administration officials, two diplomats, and four business leaders. The stakeholder selection was made by mapping from the documentary sources and a snowball approach during the interview process. All interviewees were shown a timeline of events pertaining to EU-Swiss energy affairs and were asked to comment on the sequence of events most relevant to their personal experience. The timeline can be found in Appendix C (p. 179). The timeline continued to be improved while the interviews took place, based on the content of the interviews. We took efforts to include critical voices and to balance European and Swiss perspectives. Although the interviews were a primary source of information, we triangulated the information obtained with official documents and research reports for accuracy and reliability. Interviews are cited in-text as CH# or EU# and refer to a specific Swiss or EU interviewee, respectively. Anonymity was promised to all participants due to the current political sensitivity of EU-Swiss relations.

Section 2 explains the modes of external governance and relevant hypotheses in further detail. Section 3 and 4 describe the key elements of European and Swiss energy history, respectively. Special attention is given to those developments which have been relevant in the shaping of EU-Swiss relationship. Section 5 provides a discussion of these developments using the external governance framework. The last section summarizes our results and provides a perspective on the future of EU-Swiss energy relations.

3.3 Modes of external governance

Williamson (1975) defined markets and hierarchies as distinct ‘modes of governance’, based on dispersed competition and hierarchical control, respectively. Later researchers pointed to networks as an additional mode of governance, based on reciprocal patterns of communication and exchange, contrasting and competing with markets and hierarchies (Jones, Hesterly, & Borgatti, 1997; Powell, 1990). Although this governance approach was traditionally applied to internal governance, Lavenex (2004, p. 682) argued that the governance approach is particularly useful for studying EU external relations because of its emphasis on hierarchical and horizontal, formal and informal forms of policymaking. EU external governance has been defined as “institutionalized forms of coordinated action that aim at the production of collectively binding agreements…beyond the borders of the EU and its formal, legal authority” (Lavenex & Schimmelfennig, 2009, p. 795). Using this definition, Lavenex and Schimmelfennig (2009) further defined the three ideal modes of governance in the context of EU external relations.

They firstly define hierarchical governance as a formalized, asymmetrical relationship based on the principle of domination and subordination, enforced through legally binding, non-negotiable legislation. They argue that the traditional form of hierarchy is never strictly present in an EU external governance context, as third countries retain formal sovereignty. Nonetheless, certain parts of EU external governance come close to this mode of governance, such as the European Economic Area (EEA) overarching framework agreement. They point to the existence of precise rules, formal procedures, monitoring, and sanctioning as indicators of hierarchy.

Secondly, Lavenex and Schimmelfennig (2009) define network governance as institutionalized, ongoing coordination, both formal and informal. Actors are formally equal, even if power imbalances exist, as no party is able to formally bind the other party without their consent. The presence of central institutions is a strong indicator of EU network governance, but network governance can also exist without a central institution (Provan & Kenis, 2008).

Thirdly, they define market governance as the outcome of competition between formally autonomous actors. In the context of EU external relations, this can be best seen by the competitive pressure of the Single Market. Competitive forces can drive an approximation of EU legislation or the adoption of EU standards in third countries, even without a formal requirement. This conceptualization of market governance invokes similar principles as described in the policy diffusion literature (see, e.g., Simmons et al., 2006), as the outcomes are the result of unilateral decisions of third countries in order to gain or avoid material consequences.

Lavenex and Schimmelfennig (2009) offer several hypotheses as to why certain governance forms become dominant. Observing that the mode of governance varies with structures of power relations and levels of interdependence, they hypothesize that an asymmetrical, high interdependence tends to favor hierarchical governance, whereas symmetrical, strong interdependence is most conducive to market governance. Network governance arises in situations with medium interdependence. In our analysis, we will examine whether these hypotheses hold in the case of EU-Swiss bilateralism in the area of energy. Table 3.1 summarizes the three modes of governance.

Table 3.1: Structural modes of EU external governance. Adapted from Lavenex and Schimmelfennig (2009).

	Actor constellation	**Institutionalization**	**Mechanism of rule expansion**	**Interdependence**
Hierarchy	Vertical: domination and subordination	Tight, formal	Harmonization	High, asymmetrical
Network	Horizontal: formal equality of partners	Medium-tight, both formal and informal	Coordination, negotiation	Medium, symmetrical or asymmetrical
Market	Horizontal: formal equality of partners	Loose, informal	Competition, market pressure	High, symmetrical

Note: the last column assumes the mode of governance is primarily determined by power relations.

3.4 European energy history

The history of European energy policy has been described by many authors (e.g. Hancher, 1997; Jevnaker, 2015; Meeus, Purchala, & Belmans, 2005; Vasconcelos, 2005). This section will not provide a detailed account of EU energy policy development but rather highlight the most relevant aspects of the relationship with Switzerland. Figure 3.1 shows an overview of the most pertinent events and legislation.

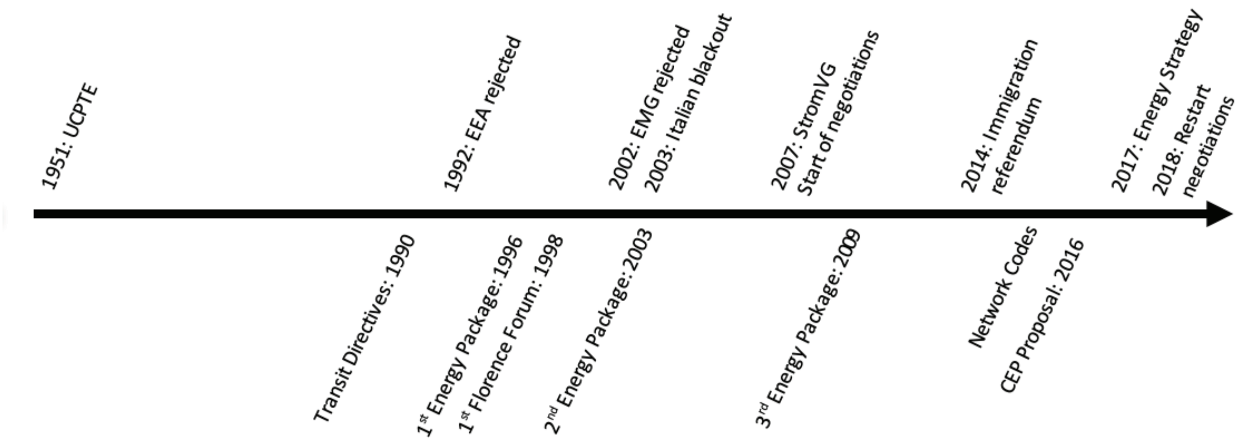

Figure 3.1: Timeline of relevant energy history of the EU (below) and Switzerland (above).

3.4.1 Transit Directives and first Energy Package

The EU took the first step towards the internal energy market (IEM) by passing the Directives on the Transit of Electricity and Gas in 1990 and 1991, respectively (Nylander, 2001). These “Transit Directives” asked Member States to facilitate cross-border trade, without, however, specifying how. Further legislation was necessary to integrate the energy markets. In 1996, the first Electricity Directive was adopted; the first Gas Directive followed in 1998. This first “Energy Package” mandated legal unbundling, a transmission system operator (TSO), and the gradual opening of markets to competition (Meeus et al., 2005). Notably absent was a compensation mechanism for cross-border trading, which was to be settled bilaterally.

Aware of the regulatory gaps created by the first Energy Package, the European Commission (EC) convened the first Florence Forum in 1998 (Vasconcelos, 2005, p. 90), which brought together all relevant stakeholders to devise regulatory solutions through consensus building. New organizations were created to facilitate this process. Examples include the Council of European Energy Regulators (CEER) and the Association of European Transmission System Operators (ETSO). Their first task was to define a mechanism for cross-border trade. In 2000, a solution was developed and presented to the EC: cross-border trades would be settled through inter-TSO compensation (ITC), considering only physical flows and compensating transit countries such as Switzerland. However, adoption of this solution was delayed until 2003 due to of fierce opposition mainly by the German government (Vasconcelos, 2005, p. 91).

3.4.2 Second Energy Package

Unsatisfied with the pace of liberalization and the remaining regulatory gaps (Jevnaker, 2015, p. 934), the EU adopted the second Energy Package in 2003. The legislative package mandated full market opening for all customers across the EU, stronger network access regulation, as well as the establishment of an independent regulator. It also created the European Regulators Group for Electricity and Gas (ERGEG), which was largely equivalent to the CEER but included the EC as an observing, non-voting member (Coen & Thatcher, 2008).

3.4.3 Third Energy Package and Network Codes

The newly established ERGEG had almost no formal power (Coen & Thatcher, 2008) and adoption of the agreed regulatory solutions remained voluntary, which the EC considered inadequate (Jevnaker, 2015, p. 934). The solutions it provided were unclear and significant regulatory gaps remained across the IEM, especially regarding cross-border mechanisms. A third Energy Package aimed to solve these problems in 2009 through stronger EU-level governance and centralized cooperation (Jevnaker, 2015, p. 935). The Agency for the Cooperation of Energy Regulators (ACER) was created to succeed the ERGEG and the European Network of Transmission System Operators for Electricity (ENTSO-E) to succeed the ETSO and the Union for the Coordination of Transmission of Electricity (UCTE). These organizations institutionalized the informal power held by their predecessors. A new legislative process was started between ENTSO-E and ACER to develop the Network Codes (NCs)—binding standards on operation, connection and market conditions (Jevnaker, 2015, p. 928).

3.4.4 Clean Energy Package

The three Energy Packages had mostly focused on liberalization, integration, and security of supply. Climate and sustainability concerns were addressed by separate legislative packages. Proposed by the EC in November 2016, the Clean Energy Package (CEP) harmonizes climate and sustainability with the rest of EU energy policy. Besides updating the targets for the 2030 horizon, the CEP legally defines new types of actors such as aggregators and local energy communities, expands the mandate of ACER, proposes an EU distribution system operator (DSO) entity, and expands the scope of the NCs (Meeus & Nouicer, 2018).

3.5 Swiss energy history

3.5.1 Before 1990

Switzerland was a main driver of European integration in the electricity sector as a founding member of the Union for the Coordination of Production and Transmission of Electricity (UCPTE)[8]. In 1958, the “Star of Laufenburg” substation was commissioned in the Canton of Aargau, connecting the electricity grids of Switzerland, France, and Germany for the first time. The UCPTE grid grew rapidly and by 1996 it crossed 19 European countries from Poland to Portugal, with the Laufenburg control center still at its core (UCTE, 2009). The Swiss companies in the UCPTE

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[8] The UCPTE changed its name to UCTE in 1999, dropping the “P” for production (UCTE, 2009).

were influential and were not restrained by the Swiss national authorities. Although national governments sometimes sent delegates to UCPTE meetings (CH1), they held no formal power within the organization.

3.5.2 1990 to 2003

In 1990, the Swiss public voted overwhelmingly in favor of giving the national government a constitutional energy mandate, which had previously been a mostly cantonal affair. In this period, the Swiss economy was stagnating, and following a referendum rejecting EEA membership in 1992, the Swiss government was exploring new ways to stimulate the economy. It was clear from the European side that the future of the electricity sector was going to be liberalized, unbundled, and competitive. Notable publications from de Pury (1995) and Cattin (1995) garnered significant media and political attention by highlighting the economic benefits of liberalization in Switzerland (CH1). A liberalization law, called the Electricity Market Law (EMG), was being drafted based on the recommendations of the Cattin report (Jegen, 2009). Although economic benefits were a main driver for the EMG, it was developed in line with the first Energy Package to ensure EU-compatibility and maintain market access (Jegen & Wustenhagen, 2001).

When the Florence Forum convened for the first time in 1998, the participating stakeholder organizations were not official EU institutions, and therefore membership was not strictly reserved to EU Member States. Thus, Swiss delegates were able to participate, unlike in the formal EU legislative process. Switzerland had less influence in the Florence Forum than it did in the UCPTE but was able to participate and represent its interests. For instance, the ITC solution proposed by the Florence Forum was co-developed and strongly advocated for by Swiss representatives as it favored transit countries (CH6). Because there was no formal TSO or regulator in Switzerland, the electricity companies and the government sent delegates to represent these roles. Their European counterparts mostly accepted this, as long as they did not push their conflicting interests too strongly (CH6). It was the same for several EU Member States—not all of them had a regulator or had fully unbundled their companies. The credibility of Swiss actors in the Florence process was based on skilled diplomacy and on the “promise” that EU-compatible domestic legislation was in development, integration would proceed, and that their presence in Florence was therefore needed (CH6).

The seven Swiss electricity companies that owned the high-voltage transmission grid set up ETRANS in 1999, an organization taking on the role of national grid operator. Creating ETRANS allowed the companies to retain ownership of their assets, as ETRANS merely coordinated their work centrally. The companies had openly been against the creation of a national grid company, afraid of losing ownership of their valuable grid assets (Bartle, 2006).

The EMG was rejected by referendum in 2002 (Jegen, 2009, p. 584). While the opposition did not appeal to an anti-European sentiment, the rejection could still be seen as a Eurosceptic outcome as the EMG was meant to streamline Swiss domestic policy with the EU. Regardless, the rejection did not elicit a strong reaction from the EU (CH1). Switzerland was still seen as a reliable country. The first Energy Package was a sort of “menu” approach where each Member State had a significant choice on how to direct their internal affairs (Hancher, 1997, p. 101). Hence, regulatory gaps were commonplace within internal EU borders and Switzerland, as an isolated case, did not raise too many concerns at that point. Additionally, technical compatibility, including regarding security measures, was assumed to be ensured through the UCTE.

3.5.3 2003 to 2014

An Italian blackout originating on the Swiss border in 2003 changed the political landscape. The blackout had an immense effect: 56 million people were left without electricity for up to 19 hours, with economic damage estimated at about €1.2 billion (A. Walker, Cox, Loughhead, & Roberts, 2014, p. 17). Switzerland was heavily criticized for not responding to the warning signals in a timely manner, as well as for not having a properly unbundled TSO (CH6; EU3). However, an official investigation showed that Switzerland had not broken UCTE rules and could thus not be held accountable for damages (UCTE, 2004). Regardless, it became clear that the UCTE rules were not strict enough to guarantee reliability, and that reliability depended on Swiss participation.

In April 2004, the Swiss companies voluntarily agreed to merge the seven transmission grids into a single control area under control of Swissgrid, a Swiss TSO (d'Arcy & Finger, 2014). This was not only in response to the European criticism but also in anticipation of a new domestic liberalization law which was sure to include a requirement for a Swiss TSO. By forming Swissgrid on their own terms, they could determine their own rules. Rather than owning the transmission grid directly, the companies took ownership of Swissgrid—it thus remains an imperfectly unbundled grid operator (d'Arcy & Finger, 2014).

Even though the first liberalization law was rejected in 2002, the Federal Tribunal ruled in 2003 that the cartel law *de facto* necessitated liberalization (Bellanger, Cavaleri Rudaz, Tanqurel, & Bellanger, 2006, p. 197). This allowed the government to propose a new liberalization law—the Electricity Supply Act (StromVG)—which passed in 2007 (Jegen, 2009, p. 584). It called for the opening of the market in two steps, the creation of a national regulatory authority (ElCom), and a national grid operator (Swissgrid). The electricity market was opened to all consumers with an annual consumption higher than 100 MWh in 2009 (Federal Council, 2013). There was no referendum for the StromVG, primarily because the second liberalization step would be subject to a possible referendum.

After the blackout, calls for stricter coordination with Switzerland intensified on both sides (CH6; CH7; EU1; EU2). Formal negotiations for a bilateral agreement on electricity started in 2007 (European Commission, 2007). The negotiations, although slow, were happening in good faith as the recent Swiss developments had consistently been EU-compatible. Pragmatism directed this indirect Europeanization: the changes not only aided in the overall security of supply and economic efficiency through enhanced EU-compatibility, but it also created goodwill by preparing for the implementation of the electricity agreement under negotiation.

Regardless of these domestic developments and the ongoing negotiations, Switzerland was slowly becoming less influential in European energy affairs. The second and third Energy Packages and subsequent creation of ERGEG and ACER in 2003 and 2009, respectively, institutionalized the network governance approach started by the EC with the Florence Forum after the first Energy Package. These organizations were now official EU organizations and therefore less open to delegates of non-Member States. This also held true for the programs that they launched, such as the Regional Initiatives, for which Switzerland was only an observer country (Jegen, 2009, p. 591). Nonetheless, when ENTSO-E was created, Swissgrid was allowed to become a member as it had traditionally been a member of the UCTE which ENTSO-E succeeded. Through ENTSO-E, Swissgrid participated in the development of the NCs.

3.5.4 2014 to present

In 2014, eleven years after the Italian blackout and following seven years of formal bilateral negotiations, the end of the negotiations was in sight, with a verbal consensus having been achieved regarding many of the issues on the table (CH5). However, all negotiations were halted in 2014 when the Swiss population voted to limit immigration from all EU countries (Jenni, 2016, p. 284). This was in direct opposition to the Agreement on the Free Movement of People (AFMP) signed a decade earlier. The EC put all bilateral negotiations, including those on the electricity agreement, on hold pending on how the government decided to implement the referendum results (European Commission, 2014). Most EU-Swiss agreements contain guillotine clauses, meaning they can all be terminated if one party terminates a single agreement.

The political relationship with Switzerland became strained (CH5; EU3). When the first NCs came into force, they had an ultimatum for Switzerland: until a bilateral electricity agreement was signed, Switzerland would be excluded from participating in the intraday, day-ahead, and balancing market coupling mechanisms of the EU[9]. Besides a loss of market opportunities, this exclusion caused an increase in unscheduled loop flows and a subsequent need for re-dispatching in Switzerland (Swissgrid, 2018).

In 2016, Switzerland implemented an AFMP-compatible version of the immigration bill in order to appease the EU (Federal Council, 2016). The open dossiers could be picked up again (European Commission, 2016). However, the relationship had changed drastically (CH5). Switzerland had become acutely aware of its dependency on the EU, and the EU was not sure how to deal with Switzerland. It was not in their interest to break all ties with Switzerland, however, they wanted to make clear that the agreements were an “all or nothing” package. The EU was dealing with several crises—a dragging economic crisis, the refugee crisis, and Brexit. Uncertainty in the relationship with Switzerland was far from desirable and the EU could not set a soft precedent in light of Brexit (Atkins & Brunsden, 2018). A sentiment of distrust had also grown in Brussels regarding Swiss politicians, as their promises and any agreements were limited by federal competencies and the possibility for referenda (CH5). Even though it was not formally ended at the time, the EU had already signaled back in 2008 that the unique “Swiss way” of association

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[9] See art. 1(6) of the Electricity Balancing Guideline and art 1(4) of the Guideline on Capacity Allocation and Congestion Management.

based on bilateral agreements was reaching its limits (Council of the EU, 2014). Preliminary negotiations on an institutional framework started in 2011 (Federal Council, 2011). However, after the 2014 referendum, all open dossiers became conditional on the institutional framework negotiations, including the electricity agreement (CH5).

Prior to 1990, when the EU started legislating, Switzerland was central and influential in European energy affairs. This stands in stark contrast to the situation in 2018, when it had become excluded from influential organizations and market mechanisms. Gradual EU institutionalization and key events such as the 2003 blackout and 2014 referendum were the main contributors. This deterioration of the Swiss position has gone hand in hand with a shift in the power balance. Whereas in previous decades the EU wanted an agreement with Switzerland because of its strong interconnection and valuable hydropower resources, it is now Switzerland that needs an agreement with the EU. Deteriorating market access could have real consequences for Swiss security of supply, while EU countries are gradually increasing their interconnection (European Commission, 2017), making Switzerland less essential as a transit country.

Contemporary Swiss energy policy is focused around the Energy Strategy 2050 (ES50). Passed by referendum in 2017, the legislative package embodies the Swiss sustainability transition: gradually phasing-out nuclear energy while supporting renewables and energy efficiency (Federal Council, 2017). This nuclear phase-out is likely to increase Swiss reliance on electricity imports, both seasonal and annual, further exacerbating this shift in power (Demiray et al., 2018; ElCom, 2018; Verhoog et al., 2018). In comparison to the CEP, which is a broad legislative package focusing on consumer empowerment, security of supply, energy market design, as well as climate and sustainability goals, the ES50 is more limited as it focuses solely on the latter. A revision of the StromVG, for which the parliamentary process started in 2018, is scheduled to address those other issues (Federal Council, 2018).

3.6 Discussion

3.6.1 Networks

Network governance can be seen early on in European energy affairs. The creation of the UCPTE, a network administrative organization, by the electricity companies, is a clear sign of network governance (Provan & Kenis, 2008). This organization was coordinating the European power grid long before the EU became involved. The UCPTE's rapid growth and the duration of its existence is a clear sign of the success of this type of coordination.

Network governance continued to be the preferred method of governance for the EU when it began legislating the energy markets. The consecutive energy packages gradually institutionalized the network governance mechanisms. Jegen (2009) shows that this institutionalization has progressively made it harder for Switzerland to participate. However, we observe an overall trend of increasing hierarchy as well, with EU legislation increasingly taking over network functions.

The Transit Directives, and to a certain degree the first Energy Package, contained few binding rules and left the Member States ample choice to coordinate and implement their own procedures and standards. The UCPTE was in the ideal position to take a leading position but failed to do so to a sufficient extent. The creation of the Florence Forum by the EC was meant to find regulatory solutions through network governance. The voluntary rule-creation in Florence was still open to representatives of invited third countries. Swiss companies, represented through ETRANS, were successfully able to represent their interests. However, the participants in the Florence Forum failed to reach consensus on the ITC, and the EU subsequently felt compelled to enforce the measure in the second Energy Package.

The 2003 blackout further showed that weak forms of coordination were not sufficient to ensure reliability in the increasingly complex grid. The EU intervened with the third Energy Package by creating a new organization, ENTSO-E, to take over the functions of the UCTE and ETSO. If the companies in those organizations had committed to binding technical rules through the UCTE, perhaps this would not have been necessary. The UCTE was a loose form of collaboration relying more on mutual trust than binding rules. Even though ENTSO-E is still a network organization, it is an EU agency mandated to create legally binding rules and procedures, introducing more hierarchy into the network. The first NCs—developed by ENTSO-E and ACER—excluded Switzerland from participation in several market mechanisms.

The formation of Swissgrid, in the wake of the Italian blackout, was a clear signal of network governance as well. Although there was no clear hierarchy enforcing the creation of a TSO, the criticism endured from other network participants—at the Florence Forum and through the UCTE—spurred this approximation of EU energy policy, even in the absence of domestic legislation. Much of the work that Swissgrid has done in the subsequent years to coordinate technical affairs through ENTSO-E can be attributed to network governance as well.

Lavenex and Schimmelfennig (2009) postulate that network governance is most favored in situations of medium interdependence, both in asymmetric as well as symmetric power relations, which seems to be consistent with our observations. Interdependence of the European electricity markets has grown continuously, both physically and economically, and as a result, pure network solutions were no longer deemed sufficient or optimal, leading the EU to introduce governance processes that were more hierarchical in nature.

3.6.2 Markets

Jegen (2009) argues that Swiss companies' successful participation in UCTE and ETSO is a form of market governance which at least partially compensates for the decline in their influence over the increasing institutionalization of EU energy policy. We argue this is not a form of market governance, driven by dispersed competition, but rather a form of network governance as it results from ongoing multilateral coordination through a central organization. The Swiss network participants are predominantly market actors but that does not imply competitive pressure is de facto the driving mode of governance.

Markets have rarely been the dominant mode of governance in EU-Swiss energy relations. Throughout most of the 20th century, energy companies remained vertically integrated companies. Since their monopolies were often legally protected, there was no competitive pressure that could incite any approach of EU-Swiss legislation. Rather, network governance coordinated the relations between companies through the UCTE as soon as trade became possible, due to the complexity of the physical infrastructure.

Nonetheless, when EU Member States started opening their electricity markets and breaking monopolies, competitive pressure arrived. One of the strongest rationales for the first liberalization law in Switzerland was EU compatibility to ensure market access (Jegen & Wustenhagen, 2001). Even though it was ultimately rejected, and liberalization did not arrive in Switzerland at that time, the Swiss companies felt compelled to change their business model. The formation of ETRANS is a clear example. The Laufenburg control center had historically been operated by EGL who therefore had longstanding relationships with foreign electricity companies. The other Swiss companies were afraid that these business relationships would become a significant competitive advantage for EGL once they were able to start trading across Europe (CH6). The Swiss companies were therefore in favor of creating ETRANS, as the control center would come under the control of all seven companies. This decision was not negotiated with any EU authority or through any network. Market pressure spurred this form of adaptation to EU energy policy in the absence of any hierarchy or network.

Other examples of adaptation to EU energy policy can be attributed, at least partly, to market pressure. Examples include the EU-compatible provisions of the StromVG and the introduction of a power exchange in Switzerland. This does not preclude domestic affairs being the main driver of these developments but merely points to the presence of economic pressure as a contributing factor. A common factor is asymmetry, as it has consistently been Switzerland which has followed EU developments, contradicting the hypothesis of Lavenex and Schimmelfennig (2009) that market governance stems from symmetrical power relations.

3.6.3 Hierarchies

Negotiated bilateralism was established as the mode of EU-Swiss coordination after Switzerland rejected EEA membership in 1992. Lavenex and Schimmelfennig (2009) would argue that this is a form of network governance, as both actors retain formal sovereignty and rule expansion is based on mutual consent. However, we argue that Swiss bilateralism has evolved into a type of hierarchical governance. When the Swiss population voted to restrict immigration in 2014, the guillotine clauses in the bilateral agreements acted as a way to enforce compliance. Formally speaking, Switzerland could have implemented immigration quotas for EU nationals as the referendum demanded, but this would have broken all bilateral agreements with the EU and therefore Switzerland refrained. The EU relationship has become an “all or nothing” package akin to the EEA or even EU membership itself, as Brexit has demonstrated. The asymmetrical power balance between Switzerland and the EU has developed into a form of hierarchical governance in those areas where bilateral agreements have been signed.

The negotiations for such an agreement in electricity have been ongoing since 2007. If successful, the scope of this hierarchy will be extended to electricity. Even though EU legislation has no formal power over Switzerland, recent EU energy legislation tries to pressure Switzerland to comply regardless—a sign that hierarchy is being established. The NCs exert strong market pressure by explicitly excluding Switzerland from market coupling on the intraday, day-ahead, and balancing markets until an agreement is signed. Market pressure has been a strong motivation for Switzerland to pass EU-compatible legislation in the past, as described in the previous section. The NCs also contain technical standards which for Switzerland are practically impossible not to follow due to its physical integration into the European power grid. This trend of increasing hierarchy, also briefly hinted at in section 5.1, is consistent with the hypothesis of Lavenex and Schimmelfennig (2009) that high, asymmetrical interdependence tends to favor hierarchical external governance.

3.7 Conclusion

We examined Swiss-EU bilateralism in energy as a case for EU external governance. This section will summarize our main findings as well as provide a discussion on the implications for future EU-Swiss relations and EU external governance.

European energy affairs have historically been coordinated through network governance. EU modes of external governance are strongly path-dependent (Lavenex et al., 2009), as can be seen in energy. Network governance remained the dominant mode of coordination when the EU started legislating. However, the trend towards hierarchy is clear in both EU internal and external governance. Other researchers have similarly pointed out that even though the EU institutionalized network governance, it has retained formal power and hierarchically enforces compliance (Coen & Thatcher, 2008; Eberlein & Grande, 2005). This trend has continued with the subsequent passing of new EU energy legislation. This steady march of institutionalization of the EU energy market has made the relationship with Switzerland increasingly asymmetric, and we observe a consequent marginalization of the role of Switzerland in European network governance, in which it had traditionally held a central role. Key events such as the 2003 Italian blackout and 2014 immigration referendum further contributed to these shifts in the mode of governance. These findings are consistent with the power-based hypotheses of Lavenex and Schimmelfennig (2009) concerning hierarchy and networks as modes of external governance, favoring hierarchy when interdependence is higher and asymmetric. Nonetheless, only network governance provides an organizational opening for the inclusion of third countries in the policy process of the EU, as hierarchy assumes an institutional relationship—which Switzerland formally does not have—and the implied absence of hierarchy in market governance precludes organizational inclusion.

The ongoing negotiations present an opportunity as well as a risk to Switzerland. The risk lies in deepening the hierarchical relationship that has emerged over the years, following the trend of hierarchy seen in internal EU affairs. If an agreement is signed on electricity, with or without an institutional framework agreement, it will likely contain an explicit or implicit guillotine clause linking it to the existing bilateral agreements, further developing the hierarchical relationship. However, the opportunity lies in the re-integration into the network governance mechanisms of the EU, in which it has historically been particularly capable in advocating its interests. The CEP expands the scope of the NCs, which are negotiated and drafted by the central institutions ENTSO-E and ACER. The CEP further proposes the creation of a DSO-entity that will also participate in the creation of the NCs (Meeus & Nouicer, 2018). Participation and voting rights in ACER and the new DSO-entity would integrate Switzerland into these legislative processes. Such inclusion will only be possible through an agreement between the EU and Switzerland. The interdependence of the EU and Swiss energy sectors will mean the second generation of NCs will have a similarly strong impact on Switzerland as the first generation, regardless of whether or not an agreement is signed.

Exclusion has not only diminished Swiss influence on legislative processes but also its market access. Historically, market pressure was a strong driver for Switzerland to unilaterally adopt EU-compatible legislation. The increasingly asymmetrical power balance between the EU and Switzerland makes it hard for Switzerland to resist such pressure and it is therefore likely that this will impact the future relationship.

However, the CEP is not included in the negotiation mandate for the EU-Swiss electricity agreement. The negotiation mandate was originally based on the second Energy Package but was extended to include the third Energy Package in 2010 (Federal Council, 2010), therefore it is possible the CEP is added at a later stage. Regardless, the second generation of NCs it proposes will be coordinated through the network agencies into which Switzerland could become a member. Thus, even if the agreement does not include the CEP, it would be able to participate in the legislative process.

It is unlikely that Switzerland will implement the CEP provisions without an agreement. Swiss and EU energy policy has increasingly diverged since the passage of the third Energy Package, and this trend will likely continue if no agreement is signed. The second generation of NCs might contain exclusion provisions, as has been the case with the first generation. The past rationale to autonomously adopt EU-compatible legislation was, for the most part, to ensure technical compatibility and market access. However, such incentives are not provided by the CEP. The way forward for EU-Swiss bilateralism thus remains politically uncertain. However, it is clear that the question of whether or not Switzerland will further diverge or integrate into the EU energy markets will depend on general EU-Swiss relations more than sectoral dynamics.

Although not the main topic of this study, our findings have implications for the relations of other third countries with the EU. The harmonization and institutionalization of the internal market, one of the core missions of EU internal policy, has given the EU increasing leverage in its relations with neighboring countries. Membership conditionality is no longer the strongest leverage over governance processes the EU has in its association with third countries. Membership in various network organizations, such as ACER or ENTSO-E in energy, and participation in pan-European policy initiatives such as electricity market coupling platforms, might be a stronger influencing factor than EU membership for countries without EU membership aspirations such as the UK or Switzerland. This increasingly asymmetric relationship means external governance processes will be more hierarchical and thus exceptions are less likely to be granted in future bilateral negotiations. The “Swiss way” of EU association was mostly negotiated in a time when the EU internal market was not as advanced as it is today and can be considered an artefact rather than a realistic option for other countries.

Chapter 4 Strategic energy reserve

This chapter contains the third essay of this thesis and is based on the preprint version of the following article:

van Baal, P. A. (2019). The effectiveness of a strategic energy reserve during the energy transition: The case of Switzerland. *Competition and Regulation in Network Industries, XX*(X), 1-26. DOI:10.1177/1783591719879365

The article was originally submitted on June 14th, 2019. After a round of peer review, the article was accepted for publication on August 29th, 2019. The article was first published online on October 8th, 2019.

4.1 Abstract

Switzerland is considering implementing a strategic energy reserve: a novel policy instrument that remunerates power plant operators for storing a minimum amount of energy stored in reservoirs, to be converted into electricity when called upon. The policy is envisioned for the winter period, when the country's large hydropower reservoirs tend to be nearly depleted. This study analyzes the impact of such a strategic energy reserve on security of supply, consumer costs, international trade, and sustainability. A hybrid simulation model is developed that combines elements from agent-based modeling and system dynamics. The simulations show that the reserve can improve short-term security of supply but does not improve long-term security of supply, as it does not impact domestic investments or reduce the import dependency in the winter period. The reserve leads to a slight increase in consumer costs, even when including the reduction in outage costs. A larger reserve is more effective at reducing the supply risk but is proportionally costly as well. Lastly, we find that the policy induces scarcity periods that would not have occurred otherwise. The reserve should thus have a high strike price to ensure it is only called upon as a last resort. We conclude that there is no structural need for a strategic energy reserve, as it only increases short-term security of supply and does not meaningfully contribute to solving the long-term structural problem. Any implementation should be done on an ad-hoc basis, conditional on a short-term generation adequacy assessment. This has the potential to minimize the associated costs while maximizing the benefits.

Keywords: strategic reserve, electricity market, energy policy, energy transition, storage, hybrid modeling, Switzerland

4.2 Introduction

The advance of intermittent renewable power sources in Europe has re-ignited concerns over security of supply (Bhagwat, Richstein, Chappin, & de Vries, 2016). This has led several countries to implement capacity mechanisms (Neuhoff et al., 2016) or maintain double structures, retaining conventional power plants as backup (Sinn, 2017). A popular capacity mechanism that has been implemented in several countries, including Sweden and Belgium, is the strategic (capacity) reserve, which keeps generation capacity out of the market, to be used in times of supply shortages. Similar to the strategic capacity reserve is a strategic energy reserve, which so far has not been implemented anywhere but might be implemented in Switzerland in the near future (SFOE, 2018a), and could conceivably be adopted in other countries if and when energy storage develops further and the policy is proven effective. A strategic energy reserve is a policy instrument that remunerates power plant operators to hold a certain amount of energy in reserve, available to be converted into electricity in times of scarcity.

Switzerland, a small Alpine nation with plentiful flexible hydropower plants and virtually no conventional fossil power plants, has committed to phasing out nuclear power, the stable base-load power source that currently provides slightly over one-third of its electricity (SFOE, 2018c), and to instead promote renewables and energy efficiency. Due to its large share of seasonally available hydropower electricity, Switzerland depends strongly on electricity imports in winter and exports in summer. Substituting nuclear power for solar power, which also has strong seasonal variation, will exacerbate this pattern. Even though the Swiss import capacity is relatively high, it is increasingly congested due to an increase in European cross-border trading. This import dependency is a growing concern because of the continued lack of electricity trading agreement with the European Union and consequent exclusion to EU market coupling (van Baal & Finger, 2019). Concerns also exist about the continued availability of winter imports when neighboring countries are themselves phasing out nuclear and coal power in favor of seasonal renewables. This situation has led the Swiss government to propose a strategic energy reserve specifically for the winter period. In Switzerland, such a reserve is assumed to increase security of supply, as this energy can be called on in winter, when the hydropower reservoirs are normally close to depletion (SFOE, 2018b). However, because strategic energy reserves are a novel policy instrument there is little research or experience to draw from regarding its actual impact. Therefore, the analysis in this study uses a hybrid simulation model, combining elements from agent-based modeling and system dynamics. Specifically, we model the impact a strategic energy reserve would have on security of supply, the cost to consumers, international trade, and sustainability. While the Swiss situation is unique, the energy transition in Switzerland is similar to other countries: promoting renewables while simultaneously phasing-out conventional baseload generation such as coal or nuclear.

This study is the first to explore the strategic energy reserve as a policy instrument. We look at its potential impact on security of supply, consumer cost, international trade and sustainability. The next section examines the strategic energy reserve in more detail by discussing its design characteristics and potential pitfalls. Section 4.4 will explain the hybrid model, describing the general simulation model and the strategic energy reserve algorithm in detail. Section 4.5 explains the scenarios we used to simulate the strategic energy reserve and the baseline with which we compare the results. The results of the simulations are then presented and discussed in Section 4.6, where the impact of the design parameters of reserve size and strike price will be separately explored, as well as the sensitivity to electricity demand growth. Section 4.7 concludes the paper, summarizing the results and offering recommendations for future research.

4.3 Strategic energy reserve

The strategic energy reserve is a novel energy policy instrument that remunerates operators of energy reservoirs for keeping a certain amount of energy in reserve. This energy can be called upon and converted in times of scarcity, preventing blackouts and increasing overall security of supply. While strategic reserves have been implemented in electricity systems in other countries, they have exclusively been strategic capacity reserves, not energy reserves. Strategic energy reserves are not yet a realistic option for many countries, as energy storage is not (yet) well-developed. Switzerland has a relatively large number of hydropower storage reservoirs – totaling approximately 8.8 TWh compared to an annual demand of approximately 60 TWh (SFOE, 2018c) – which makes it an ideal case study for this type of policy. Development of large-scale energy storage might make this policy an option for other countries in the future as well.

4.3.1 Reserve design

There are many different ways of designing strategic energy reserves. Variations can be introduced in the participation eligibility requirements, participant selection criteria, how the participating operators are remunerated, how the reserve itself is operated, and lastly, the timing and implementation of the reserve.

We analyze an energy-only strategic reserve, which means that participating power plant operators are free to use the full capacity of the power plant in the market and are only required to keep the contracted amount of energy in reserve, ready to be converted into electricity. The reserved energy is dispatched when the market price exceeds a pre-defined strike price, a common dispatch design for strategic capacity reserves (Bhagwat et al., 2016) that we implement for the strategic energy reserve as well.

The strike price should be higher than any supply or demand flexibility option, such that the reserve is only called on as a last resort. When energy is taken off the market and put into the reserve, the market price should see a slight increase in prices associated with the reduction of supply. Energy reservoir operators will bid slightly higher in the spot market because of the increase in opportunity cost, as will be explained in the next section. However, the strike price also serves as a sort of price cap, reducing scarcity prices and revenues, which potentially impacts the business model of certain power plant operators. An optimally designed strike price balances these two effects in order to leave investment signals in the electricity market unaffected.

4.3.2 Availability of reserved energy in scarcity periods

In order for a strategic energy reserve to contribute meaningfully to security of supply, the reserved energy needs to be available for use in periods of scarcity. However, a strategic energy reserve which does not place any capacity requirements on participation involves an inherent risk that the energy is unavailable. If the power plant is already running at full capacity during the scarcity period, the additional energy in reserve cannot be accessed at that same moment. The risk can be lowered if the energy reserve is spread out over many separate reservoirs, minimizing the chance that none of the reserved energy is accessible. The Swiss government specifically rejects capacity reservations, and therefore implicitly accepts this risk (SFOE, 2018b). The risk is unlikely to materialize in Switzerland, as installed capacity is almost double peak demand (Demiray et al., 2018). Thus, scarcity is unlikely to occur if there is still unreserved water in the hydropower reservoirs.

A second risk exists in defining the eligibility requirements. Technological neutrality, often seen as a desirable characteristic for policies, implies that all dispatchable power plants can participate if they can keep a type of energy, ready to be converted into electricity, in reserve: natural gas, coal, nuclear fuel, or water at altitude in hydropower plants. A nuclear power plant that continuously provides electricity cannot meaningfully increase short-term security of supply simply by having more nuclear fuel in storage. Such a plant will almost certainly already be running during the scarcity period as it has a strong financial incentive to do so, and no technical limitations. In case there are technical limitations, any energy in reserve would also be inaccessible. This argument holds for most (fossil) fuel-based power plants, as they can simply buy more fuel when their reserve runs low, assuming they have unhindered access to global primary energy markets. The only power plants that meaningfully contribute more to security of supply by participating in the strategic energy reserve are those that are at risk of running out with no possibility of replenishing the reservoirs. Hydropower reservoirs, for instance, tend to run low or even dry in winter, and they cannot easily replenish these by buying more fuel. Other examples include solar plus storage, or municipal waste incineration plants.

4.4 Model description

A hybrid simulation model has been developed for this study that builds on the same core principles of a SD model used in earlier studies (van Baal, Verhoog, & Finger, 2017; Verhoog & Finger, 2016; Verhoog et al., 2018). The hybrid model was developed on the Ventity™ 2.1 software platform and builds upon the SD-only model by integrating elements from agent-based modeling. Both ABM and SD have seen successful applications to energy systems and socio-technical transitions (Ahmad, Mat Tahar, Muhammad-Sukki, Munir, & Abdul Rahim, 2016; Li, Trutnevyte, & Strachan, 2015). The difference has been described as “modeling the forest or modeling the trees” (Milling & Schieritz, 2003). They excel in their application to energy systems and transitions because they do not rely on idealized assumptions about equilibria, optima, rationality, or perfect information like other methodologies, but instead work with tailored assumptions based on the case at hand. However, they are rarely combined, despite the theoretical benefits of combining a system perspective and agent-level interactions (Chris Swinerd & McNaught, 2012).

The model runs in chronological order in typical SD fashion, updating all variables hourly. Each individual agent has a rich internal structure based on SD architecture (stocks, flows, auxiliaries). These internal structures combined with the links between the agents (the network) form the system and its emergent behavior. On top of the chronological simulation model, agents can trigger specific algorithms ('actions') to be executed either at the end or the beginning of a timestep. Actions can contain multiple steps that will execute 'instantaneously' in the model time progression; that is before the simulation continues to the next timestep. Through actions, agents can interact with other agents or change parameters, reconfiguring the system. Agents are represented and can be interacted with in an aggregated manner, as stocks in SD, as well as individually. This integrated hybrid design allows us to add plant-level mechanics and inter-agent competition while maintaining a system perspective. The full set of equations of the model can be found in Appendix D (p. 182). Figure 4.1 provides an abstract overview of the model and the separate components of the model are explained in the section below.

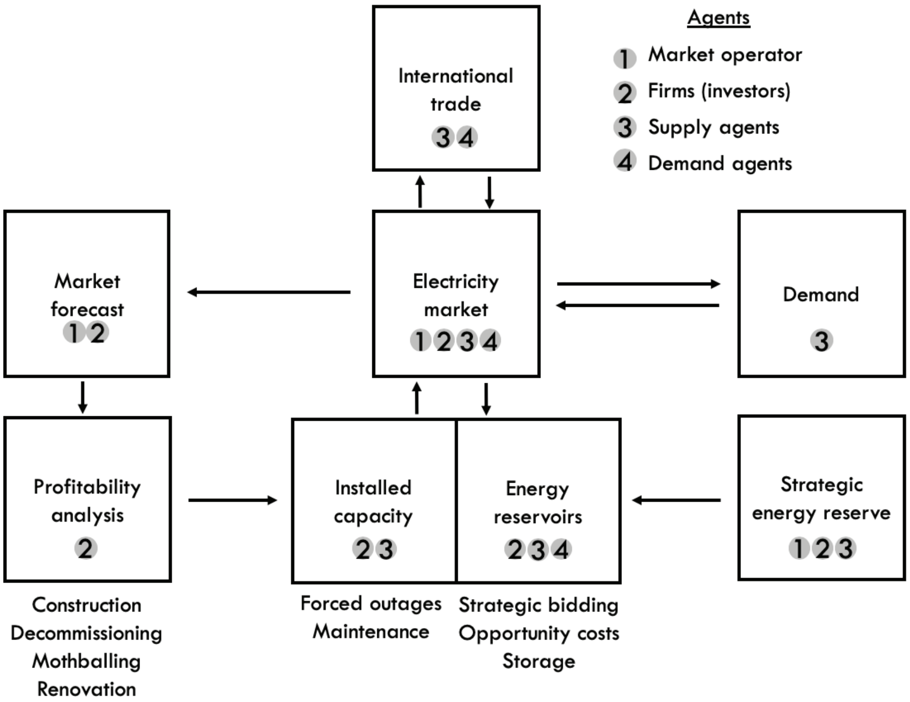

Figure 4.1: Abstract overview of model agents and modules. Arrows indicate direct interaction between modules.

4.4.1 Electricity market

The electricity spot market is the most central part of the model, and the power plants, energy reservoirs, international trade, and demand all tie into it. Based on their own market forecast, firms make economic decisions concerning their power plants that eventually impact the spot market again. Besides operating the spot market, a market operator aggregates and distributes public market data to the firms, and implements policies, including the strategic energy reserve. The market operator acts as a power exchange and collects all bids from both supply and demand agents each hour. Each bid contains a capacity (MW) and price (€/MWh) pair for the next hour, representing the maximum price a demand agent is willing to pay for the consumption of electricity or the minimum price a supply agent is willing to accept for providing electricity. The market operator clears the market by matching the bids, setting a uniform market price equal to the marginal bid, dispatching the corresponding power plants and allocating the generated electricity to the corresponding demand agents. Figure 4.2 provides a graphic overview of this process.

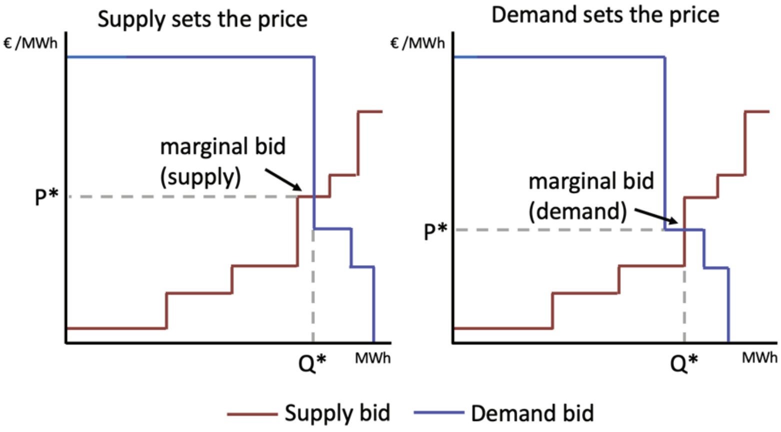

Figure 4.2: Merit-order dispatch of the spot market.

4.4.2 Supply

The supply side consists of supply agents (power plants) that deliver price and capacity bids to the market operator each hour. Power plants are required to bid their full available capacity. They choose a corresponding price based on the marginal cost of generation, which consists of the fuel price, carbon price, and other variable operating costs. Supply technologies with a finite primary energy supply and flexible dispatching, such as reservoir hydropower and waste incineration, have a premium on top of their marginal cost to reflect their opportunity costs. If one unit of electricity can only be produced once, and the timing can be influenced, the operator has the option to wait and produce the unit of electricity when prices are higher rather than lower. While the bidding price should be in the range of normal market prices, the operator has the opportunity to decrease or increase the chance of being dispatched by bidding higher or lower, respectively. Thus, their price bid should be higher than marginal costs to reflect this opportunity for higher profits. The ability to wait for higher prices is lower when the reservoir is nearly full, as the operator risks overflowing if it does not start producing electricity. Conversely, when the reservoir is nearly depleted, the operator can bid higher as it can wait longer for those prices to appear. We calculate the bidding price for each marginal unit of electricity according to Equation 4.1:

$$P_{bid}(f) = (1 - f) \cdot (P_{max} - MC) + MC$$

Equation 4.1: Bidding price.

Here f denotes the filling grade, or the percentage of the energy reservoir that is full, P_{max} is the maximum price that the investor is using as a reference to bid, and MC is the marginal cost. The bidding price scales linearly with the filling grade, asking for the marginal generation costs when the reservoir is full and approaches the maximum price when the reservoir is nearly empty. The approach is similar as that used, for instance, by Osorio and van Ackere (2016). The formula explains why there is no opportunity cost when the power plants have an assumed infinite supply of primary energy (such as gas or nuclear fuel), as this resembles a full reservoir, in which case the bidding price goes down to the marginal cost. Power plant operators change their maximum bidding price at the end of each year based on the past market performance of the plant according to Equation 4.2 and Equation 4.3:

$$P_{max}^{t} = 3 \cdot P_{ref}^{t}$$

Equation 4.2: Maximum bidding price.

$$P_{ref}^{t} = \left(3 \cdot P_{avg}^{t-1} + 2 \cdot P_{avg}^{t-2} + P_{avg}^{t-3}\right) / 6$$

Equation 4.3: Bidding reference price.

The maximum price bid in any given year t (p_{max}^{t}) is set as triple the weighted average of the selling price in the last three years (p_{ref}^{t}), where the most recent year (p_{avg}^{t-1}) is weighted three times as much as the most distant year (p_{avg}^{t-3}). This ensures that a power plant operator will always try to sell for a higher price than in previous years and is relatively quick to update the maximum bidding price if the market conditions change. The operator's success depends on the availability and prices of alternative sources of electricity. Regardless of the chosen maximum price, the owner of the power plant will automatically operate within the range of the filling grade that best allows it to arbitrage between the alternative supply options, as long as the maximum bidding price is not too high or low in comparison to the average spot price.

Production of intermittent renewables at any given hour is calculated by multiplying the installed capacity of the power plant by a yearly profile. The model contains hourly profiles for wind and solar production in MW-production per MW-installed, created by taking hourly production data in Switzerland for 2015-2017 (OPSD, n.d.) and subsequently dividing those values by the installed capacity at that time for each hour of the year. Production data of run-of-river hydropower and inflow for reservoir hydropower plants was similarly created from Swiss data for 2012-2014 (SFOE, n.d.).

All power plants have a standard forced outage rate (FOR) of 0.04, with a mean time to repair of 67 hours, in line with averages from other studies (Mohanta, Sadhu, & Chakrabarti, 2004). Every hour, a power plant has a small chance of being forced offline. If this happens, the plant will be offline for 67 hours before resuming operation. A FOR of 0.04 means that a power plant will be offline for an average of 4 percent of the year. Nuclear power plants are the only technology that also have planned outages (or maintenance). Maintenance periods are scheduled for the summer months with as little temporal overlap between the different nuclear plants as possible. Maintenance last approximately 1.5 month for each power plant, in order to bring the overall utilization factor of the nuclear plants in line with historically observed values (SFOE, 2018c).

4.4.3 Demand

The demand side is modeled similarly to the supply side, in that each demand agent supplies price and capacity bids to the market operator each hour. Demand agents represent consumer load, demand response, interruptible contracts, and the storage demand. The price bid of consumer load (the bulk of the demand) is set to the theoretical Value of Lost Load (VOLL), which we set constant at 3000 €/MWh – the maximum price allowed in the EPEX market[10] and in line with other studies (Osorio & van Ackere, 2016). Since this is much higher than any other supply or demand option, this part of demand is the most inflexible. If there is not enough available power supply to meet demand, the 'marginal bid' will always be that of the consumer load, setting the price at VOLL, constituting a supply shortage or blackout. The cost of outages, defined as the product of the VOLL and the amount of load not served, is thus included in the modeled electricity price (Bhagwat et al., 2016). The consumer load at any given moment is generated from multiplying a yearly profile by the annual total load. The annual total load grows linearly from the observed value in 2017 (SFOE, 2018c). Our baseline scenario implements a growth percentage of 1 percent; other growth percentages are explored in Section 4.6.7. The yearly profiles were constructed by dividing the hourly values of consumer load for 2015-2017 in Switzerland, obtained from ENTSO-E (n.d.), by the annual total load. Using fixed yearly profiles in this way means the load curve for consumer load is mostly exogenous. However, demand for demand response, interruptible contracts, storage, and exports is fully endogenous, so the demand side is still relatively flexible. We will explore the impact of demand response in one of our scenarios.

Demand response operators have a fixed price bid, displacing their demand to a later moment when the electricity price is lower than their bid. Their capacity bids are subtracted from the consumer load. Interruptible contracts, which represent large (industrial) consumers that choose not to consume electricity when a certain price is reached, do not displace their abated consumption to a future time period. We assume approximately 5 percent of peak electricity demand is on an interruptible contract, at a price of 800 €/MWh, which is within the range of estimates by other studies (Cepeda & Finon, 2011; de Vries & Heijnen, 2008). Storage demand agents, representing pumped hydropower, are directly coupled to a supply agent and place their price bids based on the same opportunity cost as their supply equivalent, taking into account round-trip efficiency losses. In this way, storage operators buy and sell electricity as much as they can to maximize their own profits (Densing, 2013).

4.4.4 International trade

International trade functions within the merit order curve as supply (import) or demand (export) agents. There are supply and demand agents to represent each neighboring country. In the case of Switzerland, these are Germany, Italy, and France. Their capacity bid is the Net Transfer Capacity, which can change every hour, and the

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[10] The European Power Exchange (EPEX) is the dominant power exchange in Switzerland and also operates in Austria, Germany, France, Belgium, Netherlands, Luxemburg, and Great Britain.

price bid is the foreign spot price, which also varies hourly. At each hour of simulation, the NTC value for each country is calculated by multiplying the maximum NTC by a yearly profile. The hourly foreign spot price is calculated similarly by multiplying an annual average spot price by a yearly profile. The profiles were created by taking hourly NTC and spot price values for 2015-2017 from the ENTSO-E Transparency Platform for each neighboring country (ENTSO-E, n.d.), and dividing each hourly value by their yearly average (prices) or maximum (NTC). These profiles do not change over the run of the simulation, meaning that the foreign prices are exogenous and are not dependent, for instance, on how much is being traded with Switzerland. The underlying assumption is that the Switzerland is a price taker on the international electricity market. However, the annual mean spot price and maximum NTC values can change. Future maximum NTC values are taken from the ENTSO-E Ten Year Network Development Plan (ENTSO-E, 2014). We implement a simple linear growth percentage for the foreign spot prices. The Swiss domestic electricity price is heavily determined by the foreign spot price developments because of the difference in market size[11]. Since we implement foreign prices as exogenous scenarios, we use indicators based on the difference of the national and foreign spot prices to look at the reserve effectiveness, rather than the absolute spot price in Switzerland. We discuss these indicators in more detail in Section 4.6.1.

Part of the international trade is also done via so-called long-term contracts (LTC), which are fixed-price call option contracts with French nuclear operators and have long been an important part of the business models of Swiss electricity companies. These LTC have their own supply agents and compete for NTC with the normal trade entity. The LTC will be slowly phased out, as they are due to expire in the coming decades and will not be renewed (VSE, 2012). We assume a strike price of 35 € per MWh for these LTC, in line with other studies (Osorio & van Ackere, 2016).

Some political uncertainty exists regarding the Swiss relationship with the EU, which impacts electricity trading conditions for Switzerland as all neighboring countries are EU Member States (van Baal & Finger, 2019). Notably, the exclusion to so-called market coupling causes an increase in unscheduled power flows, or ‘loop flows’, through Switzerland, that reduce the available import capacity. While this paper is not intended to be a political analysis, electricity imports strongly contribute to security of supply in Switzerland, so the impact of these loop flows must be considered. We decide to implement a reduction of 30% of NTC, a value resembling the actual situation in Switzerland (ElCom, 2017). That value is kept constant in the future, not further aggravating or alleviating the political situation. As loop flows are expected but are by nature unscheduled and unpredictable, we model half of the NTC reduction as a constant, flat reduction, while the other half is stochastic, modeled as forced outages of the import supply agents similar to power plant outages.

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[11] 62 TWh of electricity was produced in Switzerland in 2017, compared to 529 TWh, 549 TWh, and 296 TWh in France, Germany, and Italy, respectively (Fraunhofer ISE, 2018; RTE, 2018; SFOE, 2018c; Terna, n.d.)

4.4.5 Investors

Investors are economic decision-making agents, impacting the long-term development of the electricity market. Investors base their decisions on financial analyses based on their own information. They have access to the general market data provided by the market operator and plant-level data for the power plants they own. Investors base their decisions based on the profitability index as shown in Equation 4.4:

$$PI = \frac{NPV}{investment\ cost} = \frac{\sum_{n=0}^{N} \frac{C_n}{(1+r)^n}}{investment\ cost}$$

Equation 4.4: Profitability index.

Here C_n denotes the cash flow (profits or costs) at period n, and r is the discount rate, which we implement as the sum of the weighted average cost of capital (WACC) of the investor and a risk premium that depends on the type of investment. The profitability index is compared to a hurdle rate to decide whether or not an investment decision is made. For simplicity, we keep the hurdle and discount rates constant. Investors forecast prices five years into the future using basic linear trend extrapolation on the past three years of performance of their assets, correcting for expected changes in installed capacity. These include all capacity currently in construction and all capacity expected to reach the end of its operational lifetime within three years.

Investors have the ability to make financial decisions: apply for permits or invest in new power plants, or mothball, renovate, or decommission existing power plants that they own. When the profitability index of a new power plants exceeds the investor hurdle rate, the investor will invest decide to invest, starting the construction of a new power plant, if it already has the permit to construct such a power plant. If not, the investor will apply for a permit. Permits are granted after a specific permitting time (see the appendix to this article, section 4.8, p. 92) or rejected if there is no more domestic potential in the case of wind or solar. Such limits are implemented (Osorio & van Ackere, 2016) but are not reached in any of our simulations. Permits expire if the investor does not commit to invest within a certain number of years, which we assume is three years. It is important that these two decision points exist for each new power plant, because the project profitability might change between the two moments: a power plant can be taken offline, another investor can start constructing a new power plant, or the policy (subsidy) environment can change (Vogstad et al., 2002). Endogenous investments are made for wind, solar, and combined cycle natural gas. Investments in reservoir, pumped storage, and run of river hydropower are implemented exogenously in line with projections of the Swiss government (Demiray et al., 2018), because of their limited expansion potential (SFOE, 2012). Other power plants are not considered for investments.

If a power plant is not profitable in the next year – meaning the expected profits do not exceed the yearly fixed operating costs – the investor will mothball the power plant for one year, temporarily placing it out of use. If a power plant is at least 10 years old, and not expected to be profitable next year nor at any time in the coming 5 years, the investor will decommission the power plant. If the power plant has less than 5 years remaining operational lifetime, the investor can decide to renovate the power plant. If the renovation profitability index exceeds the investment hurdle rate of the investor, the plant is renovated. Renovation extends the operational lifetime by 5 years and is assumed to cost 25% of the original investment cost. The option to renovate exists also for the nuclear power plants, as the timing for the phase-out is only indicative and the schedule is therefore not certain (van Baal et al., 2017). All power plants are decommissioned at the end of their operational lifetime.

4.4.6 Strategic energy reserve implementation

The strategic energy reserve policy has not been finalized in Switzerland, so the model implementation has to make certain assumptions. The implementation of the storage reserve is done by the market operator, who collects participants' bids specifying an amount of energy (MWh) and price (€/MWh) at the start of October. Only reservoir hydropower and waste incineration plants can participate, in order to combat the risks described in Section 4.3.2. Participants will be chosen based on the price element of their bid, the lowest first, until the energy target of the reserve is met. The marginal bid will set a uniform price per MWh to remunerate all participating supply agents. The energy target or size of the reserve is set in advance. The reserved energy will be released, meaning operators can bid the energy into the market normally, after the winter period (start of April). The total policy cost of the reserve will be the remuneration paid out to the participating supply agents, less any revenues received from selling the reserved water at the strike price, as this will go to the market operator.

Supply agents make their bids for the strategic energy reserve based on the expected lost profits by participation. The lost profits are calculated by taking the markup—the selling price above the marginal costs of production—when selling the energy at the opportune moment, when prices are high (winter), minus the markup when selling the energy at a less opportune moment, when the energy is released (summer). For this reason, supply agents use the difference between the summer and winter selling prices observed in the year before to bid. The market operator will allow a maximum of 30 percent[12] of the storage capacity of a power plant to be in the reserve, to avoid losing the production capacity of that power plant on the spot market too early. Storage operators will always bid the maximum energy they are allowed to offer.

Participating supply agents keep their reserved energy in stock and use the remaining energy to bid into the spot market as normal. However, the opportunity cost changes, because the reserved energy cannot be used. Equation 4.5 shows how the bidding behavior changes. f_{bid} denotes the filling grade used for bidding, and E is the quantity of energy in the reservoir. The equation shows that a high amount of reserved energy decreases the filling grade (since $E < E_{maximum}$) and thus increases the overall bidding price (Equation 4.1).

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[12] In reality, this might still be relatively high if the reserve size as a percentage of total reservoir capacity is much smaller than that. For comparability reasons, the main scenarios use a fixed value. In Section 4.6.6, various reserve sizes are explored.

$$f_{bid} = \frac{E - E_{reserved}}{E_{maximum} - E_{reserved}}$$

Equation 4.5: Filling grade.

4.5 Scenarios

We first test the effectiveness of a strategic energy reserve in a business as usual scenario ('BAU') which does not have any additional policies. The initial conditions are modeled after the Swiss electricity system of 2018. The future technology costs are implemented as the average or mean values projected by the National Renewable Energy Laboratory (NREL, 2018), and carbon costs as forecasted by the Swiss government (Demiray et al., 2018). The full set of initial conditions can be found in the appendix to this article (Section 4.8). The annual electricity demand growth rate is set at 1 percent[13], and the annual growth rate of foreign spot prices at 1.5 percent, in line with long-term historically observed values.

In a second scenario ('RES'), the effectiveness of a strategic energy reserve is explored if new renewable energy sources are simultaneously promoted through government policy, such that the targets of the Swiss government are met. There are many different types of renewable promotion schemes possible, but the exact type of promotion is not relevant to our study as we have not sought to assess the effectiveness or cost of such a policy. The RES scenario assumes the policy works as intended. A dynamic subsidy on renewable electricity production is implemented that remains high enough to make both wind and solar profitable throughout the simulation and disappears when the investment targets are met. In this way, the targets are met, over-subsidization will not happen, while subsidy-free investments above the target remain possible if the market conditions allow. Other than the renewables promotion policy, the RES scenario is identical to the BAU scenario.

In a third and last scenario ('DR'), the effectiveness of a strategic reserve in the presence of a growing share of demand response is tested. A separate scenario is chosen for demand response because it has the potential to significantly contribute to security of supply (Khan, Verzijlbergh, Sakinci, & De Vries, 2018), while the high uncertainty that surrounds its potential scale and profitability makes implementing it via endogenous investments difficult. In the DR scenario, demand response is assumed to grow linearly such that by 2035, 10 percent of peak demand is covered by demand response. This estimate was made looking at the potential of demand response in developed countries (Gils, 2014). Demand response replaces regular, inflexible, consumer load in the model, meaning there is no increase in total power demand but only an increase in demand flexibility. A price of 500 € per MWh is assumed for all demand response assets, lower than the interruptible contracts but higher than most supply options. The DR scenario is fully equivalent to the BAU scenario other than this exogenously forced development of demand response.

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[13] Different demand growth rates are explored separately in Section 4.6.7.

For each of these scenarios, baseline simulations ('BL') are run and compared with the results of simulations with strategic energy reserve ('SER'). All simulations run from 2018 to 2035, with the strategic energy reserve implemented in 2020 until the end of the simulation. To account for the stochastic nature of the forced outages, 300 simulations are run for each setup. After 300 simulations, no quantitative differences were found.

The strategic energy reserve size tested in the main scenarios is 0.80 TWh. This is the equivalent of approximately five days of Swiss domestic demand and approximately 9 percent of the total storage capacity of all Swiss hydropower reservoirs, and within the range the Swiss government has explored (SFOE, 2018b). However, both larger and smaller reserve sizes are conceivable. Therefore, the impact of the reserve size on the reserve effectiveness is separately explored in Section 4.6.6.

The strike price should at least be higher than any supply or demand flexibility option, to ensure the reserve is only called on as a last resort. A strike price of 2500 €/MWh is assumed in the main scenarios, which is higher than any other supply option. Determining an optimal strike price leaving investment signals unaltered, as described in Section 4.3.1, is beyond the scope of this article. However, a range of different strike prices is explored in Section 4.6.6.

4.6 Results and analysis

4.6.1 Indicators

This section discusses the results of the simulations. The effectiveness of the strategic energy reserve is evaluated with 10 different indicators, which are classified into four groups: security of supply, cost, trade, and sustainability. For security of supply, the following two indicators are explored:

- [SH] *Shortage hours* (hours per year): the average number of hours of shortage per year.
- [DD] *Dispatch duration* (hours per year): the average number of hours the strategic energy reserve was called upon per year.

For cost, the following two indicators are explored:

- [RC] *Reserve cost* (million € per year): average cost of the reserve, in million per year, consisting of the remuneration to the reserve participants minus any revenue made from selling the reserved energy at the strike price.
- [CC] *Consumer cost* (€ per MWh): sum of the average electricity price and the reserve cost divided by the annual consumption.

For trade, the following four indicators are explored:

- [PD] *Foreign price difference* (€ per MWh): the yearly average difference between the domestic average electricity price and the metric average of the electricity price in neighboring countries.
- [TD] *Trade deficit* (million € per year): the net sum of revenues resulting from importing (+) and exporting (-).
- [AI] *Annual energy independence*: part of demand met by domestic production, calculated by dividing annual demand minus the net imports by the annual demand.
- [WI] *Winter energy independence*: part of demand met by domestic production in winter (January through March), calculated by dividing the total demand in winter minus the net imports in winter, divided by the total demand in winterept.

Lastly, for sustainability, the following two indicators are explored:

- [RE] *Renewable energy production* (TWh): the production of wind and solar combined in the final year of simulation.
- [GP] *Gas production* (TWh): the production of natural gas power plants in the final year of simulation.

Table 4.1: Results of main scenarios. Mean values and 90% confidence interval for each indicator.

Indicator	**Unit**	**BAU-BL**	**BAU-SER**	**RES-BL**	**RES-SER**	**DR-BL**	**DR-SER**
Security of supply							
SH	hour/yr	0.03 (0.00-0.13)	0.03 (0.00-0.12)	6.11 (0.00-24.83)	1.64 (0.51-1.87)	0.01 (0.00-0.05)	0.02 (0.00-0.07)
DD	hour/yr	NA	0.30 (0.00-1.18)	NA	6.13 (0.00-25.15)	NA	0.12 (0.0-0.49)
Cost							
RC	M€/yr	NA	46.48 (25.07-79.08)	NA	66.09 (31.94-128.0)	NA	46.27 (25.15-79.17)
CC	€/MWh	80.80 (61.10-106.5)	81.39 (61.63-107.4)	72.98 (58.10-101.6)	73.98 (58.67-102.2)	80.85 (61.17-106.5)	81.29 (61.63-107.0)
Trade							
PD	€/MWh	22.23 (7.75-42.02)	22.11 (7.82-42.01)	14.41 (4.26-37.11)	14.42 (4.50-36.08)	22.28 (7.83-42.00)	22.02 (7.83-41.57)
TD	B€/yr	1.13 (0.54-19.3)	1.13 (0.55-1.94)	0.73 (0.25-1.62)	0.73 (0.27-2.72)	1.13 (0.55-1.93)	1.13 (0.55-1.94)
AI	-	0.86 (0.81-0.92)	0.86 (0.81-92)	0.93 (0.87-0.99)	0.93 (0.88-0.98)	0.86 (0.81-0.92)	0.86 (0.81-0.92)
WI	-	0.65 (0.64-0.67)	0.65 (0.60-0.67)	0.67 (0.65-0.69)	0.67 (0.65-0.69)	0.65 (0.64-0.67)	0.65 (0.64-0.67)
Sustainability							
RE	TWh	10.71 (10.10-11.36)	10.57 (10.09-11.15)	13.51 (12.90-13.90)	13.50 (12.90-14.20)	10.69 (10.10-11.36)	10.55 (10.10-11.15)
GP	TWh	0.88 (0.83-0.93)	0.87 (0.80-0.94)	0.79 (0.70-1.02)	0.80 (0.67-1.04)	0.88 (0.82-0.93)	0.87 (0.79-0.93)

Table 4.1 shows the results of the simulations. Values for the indicators are averaged over the 15-year period that the strategic reserve is active in our simulations, 2020-2035, except for the sustainability indicators RE and GP, which are based only on the final year of simulation. The results for each group of indicators are discussed in the following sections.

4.6.2 Security of supply

In the BAU scenarios we find virtually no security of supply issues, with an average of 0.03 shortage hours per year in both the baseline and the reserve scenario. It is to be expected in any system with stochastic plant outages to find at least a low number of shortages, given there is a small probability of critical power plants shutting down simultaneously. This effect does not go away when a strategic energy reserve policy is in place, which explains why the value is the same in both scenarios.

We find a more significant number of shortages in the RES scenarios. This is an interesting finding on its own, as these scenarios have a higher amount of domestic supply because of the renewable subsidy. Apparently, the presence of the intermittent renewables introduces some supply risk. The bulk of new renewables is solar, production of which is mostly done in summer and does not significantly contribute to security of supply in winter. The reserve functions as intended and reduces the risk of shortages significantly: from 6.1 to 1.6 hours per year.

Interestingly, we find that the dispatch duration in the SER scenarios is somewhat higher than the shortage hours in the baseline for all scenarios. This effect is minimal in the RES scenario, but considering not all shortage hours are prevented, it indicates shortages were prevented that would not have happened without the reserve in place. This can happen if generation capacity is taken off the market early because of the energy reservation, creating scarcity on the market that can be solved by releasing the energy again, a risk identified in Section 4.3.

4.6.3 Cost

The reserve costs an approximate 46 million euro per year in the BAU and DR scenarios. This is higher than, but in the same order of magnitude as, the costs envisioned by the Swiss government, which estimate the costs for a 0.775 to 1.525 TWh reserve at 15-30 million CHF (SFOE, 2018b). Counter-intuitively, when the reserve gets dispatched more to prevent shortages (RES scenarios), the total cost is higher. Intuitively, the cost should be lower as the earnings from selling the energy at the strike price remunerate the market operator and thus contribute to lowering the total cost. However, the presence of supply shortages also means the electricity price will be higher overall because of scarcity, even before the strategic reserve gets dispatched. Scarcity prices in winter increase the seasonal price difference, which is what hydropower operators use to make their bids for the strategic energy reserve. Consequently the compensation they receive increases, making the reserve more costly.

The consumer cost is marginally higher in all scenarios with the reserve compared to the baseline. The consumer cost is the sum of the electricity price and the tariff rider to pay for the reserve cost, if the reserve is active. This tariff rider assumes the cost is borne equally by all consumers and is thus simply the reserve cost divided by the total annual demand. Note that the electricity price includes the cost of outages, as all lost load is priced at VOLL. In theory, the strategic energy reserve could reduce the consumer cost by the reduction of shortages and associated cost of outages. The reserve strike price of 2500 €/MWh is close to the VOLL of 3000 €/MWh, which means this effect is likely small. It is therefore not surprising the consumer cost is higher in all scenarios with the reserve compared to the baseline. The RES scenarios show that renewables depress the average electricity price and thereby the consumer cost, even if the risk of outage and subsequent higher costs of outage are included.

4.6.4 Trading conditions

We do not find significant changes in cross-border trade conditions because of the strategic energy reserve. The policy has no impact on energy dependence, either over the year (AI) or during the winter period (WI). This can be expected given that the policy is not designed to promote new investments. However, considering one of the rationales behind the policy was to increase security of supply in winter, the policy cannot be considered a long-term solution, as it does not contribute to structurally improve the situation.

The average electricity price in Switzerland is higher than in the neighboring countries (PD) in all scenarios. Nuclear energy currently serves as baseload electricity in Switzerland. The phase-out of this nuclear capacity turns Switzerland into a net importer. The flexible hydropower plants will then more often serve to meet peak demand when electricity is already being imported. Hydropower operators can then bid higher than the import price, whereas before they would have competed with imports for peak demand and would have had to bid lower.

4.6.5 Sustainability

We do not find a strong effect on sustainability indicators because of the reserve. In all scenarios we find there are slightly fewer renewables in the scenario with the strategic reserve compared to the baseline, but the effect is too small to be conclusive. Similarly, there is virtually no difference in the amount of electricity production from gas power plants. What little production there is comes from the already existing thermal power plants; none of the simulations found new investments in thermal power plants. The target of 14.4 TWh renewables by 2035 is almost met in the RES scenarios, which is to be expected considering delays in construction and permitting and the way the subsidies are implemented. Interestingly, the BAU and DR scenarios have well over 10 TWh of renewables by 2035 as well, showing that considerable investments in new renewables will happen regardless of the subsidy, but that the targets will not be met without government support.

4.6.6 Impact of design parameters on reserve effectiveness

The reserve size of 0.80 TWh and the strike price of 2500 € per MWh were implemented in all the main scenarios. In this section, we explore the impact of these parameters. We explore additional reserve sizes of 0.16 TWh, 1.60 TWh and 2.40 TWh. These are the approximate equivalents of 1, 10, and 15 days of Swiss electricity demand, respectively. A reserve size higher than 2.40 TWh is improbable as this already represents about 27 percent of all hydropower reservoir storage capacity in Switzerland. We explore additional strike prices of 2000, 1500, 1000, and 500 € per MWh. We implement these design parameters in the RES scenario, as the reserve was dispatched most frequently in this scenario and so the impact of the parameters should be most visible. The results for the reserve size and strike price are plotted in Figure 4.3 and Figure 4.4, respectively.

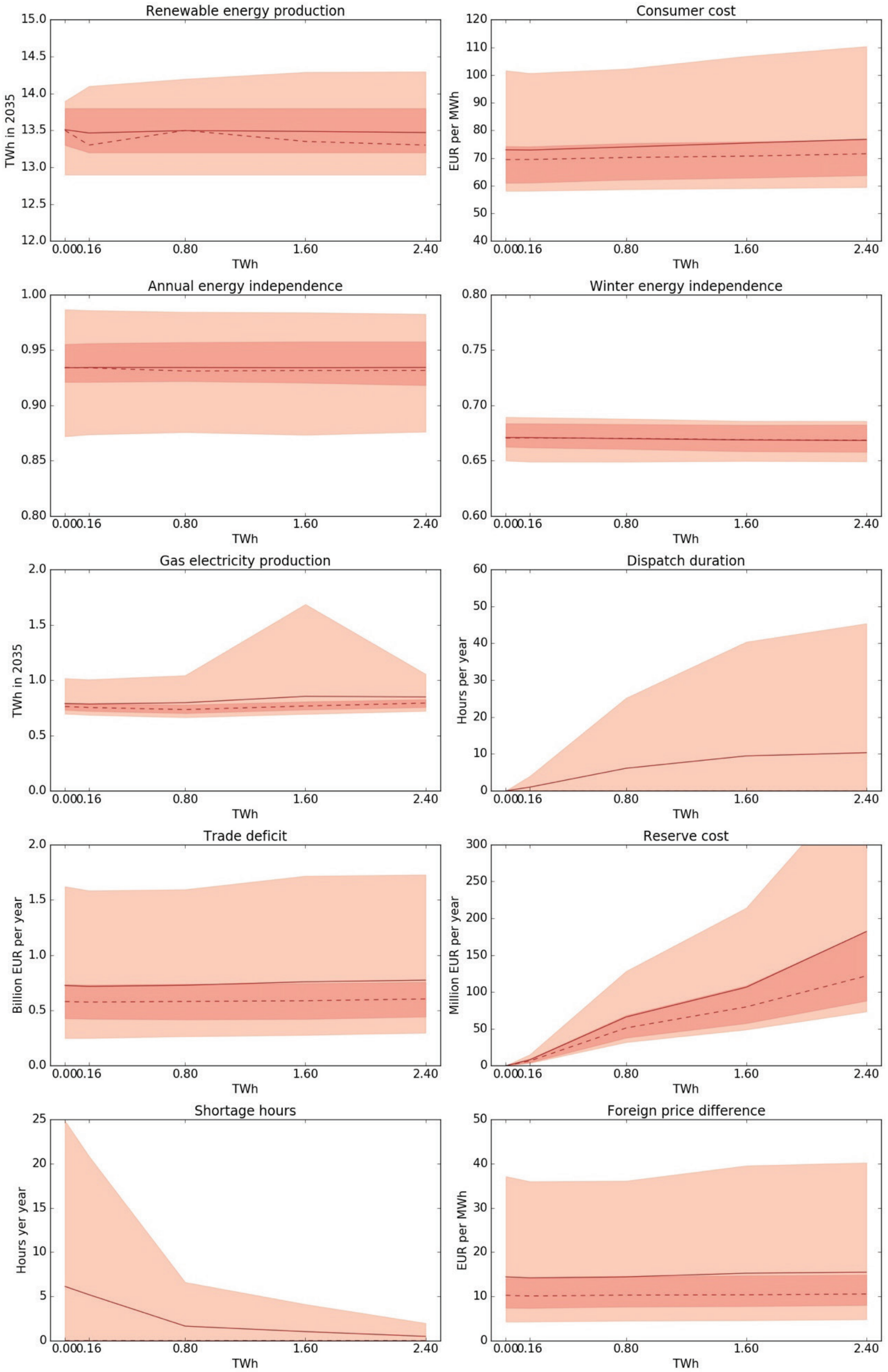
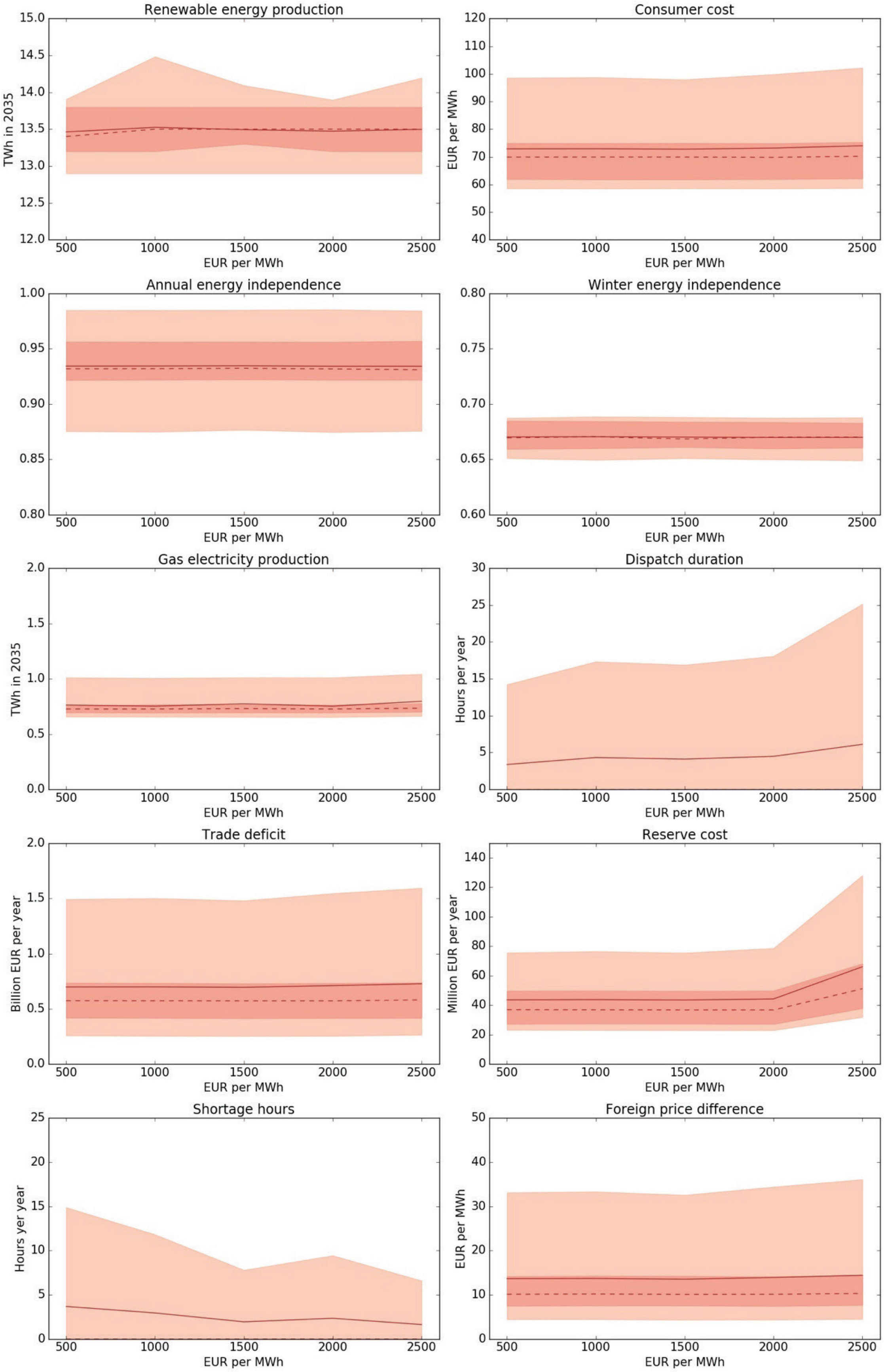


Figure 4.3: Results of RES-SER simulations with varying reserve size. Values shown are means, medians (dashed lines), 50% and 90% confidence intervals.



Renewable energy production

Consumer cost

Annual energy independence

Winter energy independence

Gas electricity production

Dispatch duration

Trade deficit

Reserve cost

Shortage hours

Foreign price difference

Figure 4.4: Results of RES-SER simulations with varying reserve strike price. Values shown are means, medians (dashed lines), 50% and 90% confidence intervals.

The reserve cost, dispatch duration, shortage hours, and consumer cost are the indicators that are most impacted by the change in reserve size. The other indicators remain largely the same independent of the reserve size, although a slight upward trend can be seen in the foreign price difference and trade deficit. The reserve cost is found to increase linearly with the reserve size: a strategic energy reserve of 2.40 TWh costs 182 million € per year, approximately three times as much as the 0.80 TWh reserve.

The dispatch duration increases with the reserve size, with the curve being concave rather than linear like the reserve cost. The dispatch duration is always higher than the number of shortage hours found in the baseline. This seems to confirm the hypothesis that the strategic energy reserve creates, and remediates, scarcity periods, although this effect does not seem to grow proportionally when the reserve size increases. The shortage hours have a negative concave relation to the reserve size. The largest difference in shortage hours is between 0.16 TWh and 0.80 TWh, whereas the difference between 1.60 TWh and 2.40 TWh is comparatively small. These decreasing marginal benefits to the reserve size hint at an optimal reserve size that minimizes costs but maximizes benefits in terms of the reduction in shortage risk. However, from a social perspective, the consumer costs are always higher compared to the baseline, indicating that consumers are better off accepting the small risk of supply shortages rather than paying for the strategic energy reserve. This is based on a VOLL of 3000 €/MWh, which is based on the current maximum spot price in the EPEX market but is nonetheless a relatively low value of VOLL and too simplistic for prolonged outages (Ratha, Iggland, & Andersson, 2013). This implies that the true cost of outages could be higher. Therefore, it is not possible to conclude definitively that a strategic energy reserve is not cost-effective.

Changes in the strike price most affect the shortage hours, reserve cost, and dispatch duration. The other variables mostly remain stable. Lowering the strike price increases the number of shortage hours. At a very low strike price (e.g. 500 € per MWh), the number of shortages is only marginally lower than in the baseline scenario. This is consistent with the purpose of the strategic energy reserve. A high strike price ensures the reserve is only used as a last measure when all other options have been exhausted. Lowering the strike price also seems to slightly decrease the reserve cost. However, this effect seems to level off for strike prices lower than 2000 € per MWh. A lower strike price should mean that the reserve gets dispatched faster, as the electricity spot price does not have to rise as high before the reserve gets called on. While an increase in dispatch duration would be expected with lower strike prices, this does not seem to be the case. We find a slight decrease in dispatch duration at a lower strike price.

4.6.7 Sensitivity to electricity demand

In this section we explore how demand growth impacts the reserve effectiveness. Future electricity demand is an uncertain parameter, as there are simultaneous efforts to promote energy efficiency, reducing the electricity demand, but also to electrify heating and mobility services, potentially increasing electricity demand.

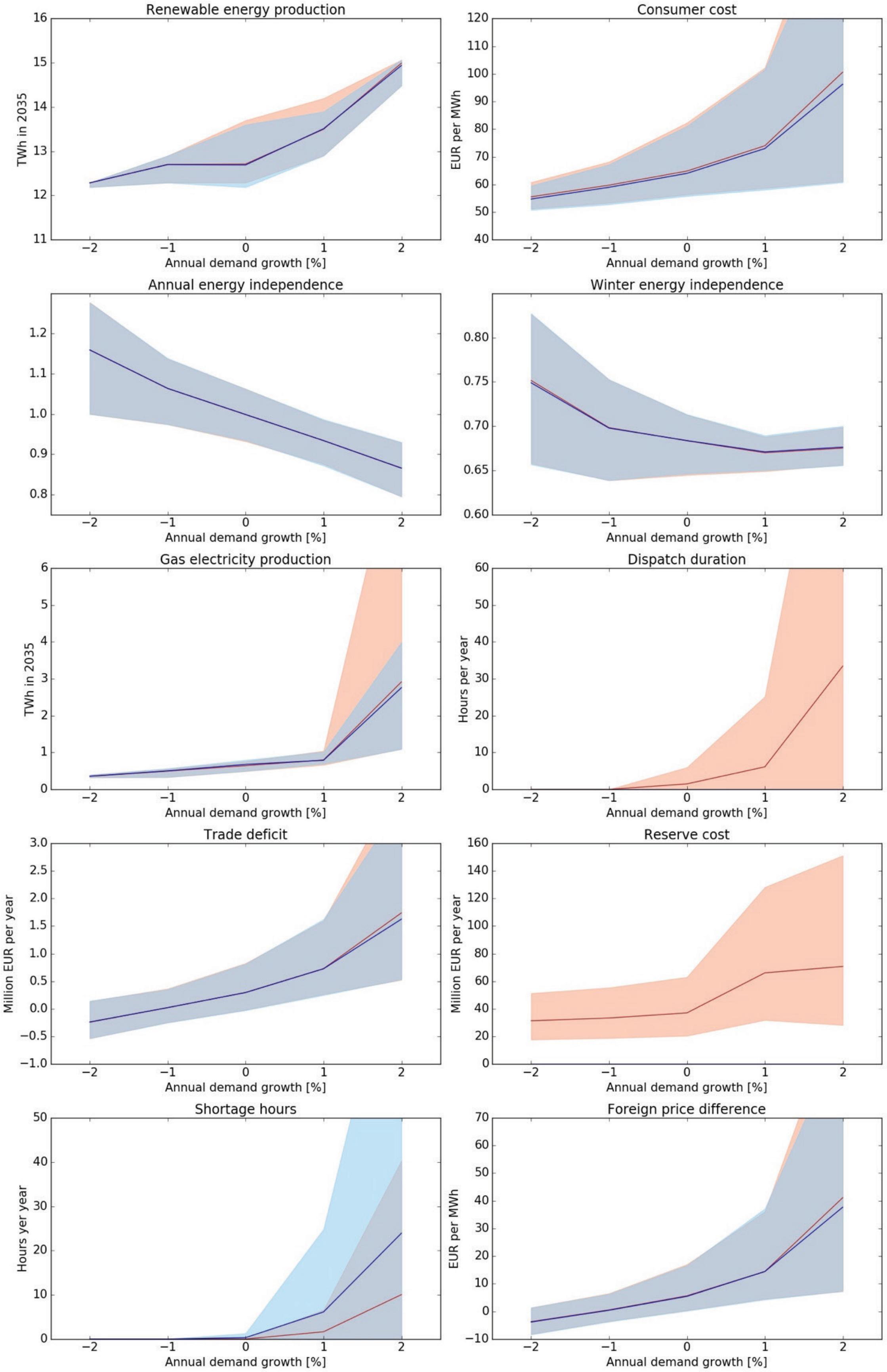


Figure 4.5: Results of RES-SER (red) and RES-BL (blue) simulations with varying demand growth rates. Values shown are means and 90% confidence intervals.

In our main scenarios, we implemented an annual electricity demand growing at a pace of 1 percent per year. Here we explore demand growth percentages of between -2 and +2 percent. Since the baseline changes when we change the demand growth, we simulate new baselines (RES-BL) as well as new scenarios with the strategic energy reserve (RES-SER) for each demand growth percentage. The results are plotted in Figure 4.5.

As is immediately visible, almost all indicators are significantly impacted by the demand growth, as expected. Demand growth has a positive relation with the indicators for consumer cost, foreign price difference, renewable and gas electricity production, trade deficit, and shortage hours. It has a negative relation with annual and winter energy independence. In the simulations with a strategic energy reserve, higher demand growth induces a higher reserve cost and dispatch duration. In the highest demand growth scenario, shortage hours are proportionally reduced by the strategic energy reserve. There are still approximately 10 shortage hours in the scenario with the highest demand growth rate. This indicates that higher demand might warrant a larger strategic energy reserve to reduce the risk of supply shortages to an acceptable level.

The dispatch duration is significantly larger than the shortage hours in the baseline scenarios, for all demand growth rates. We even observe reserve dispatches while the baseline did not have any shortage hours, in the lower demand growth scenarios. This confirms what the main simulations already showed: that the strategic energy reserve can cause scarcity that would not have occurred without the reserve. The consumer cost with the reserve is slightly higher for all demand growth percentages, as we found for the main scenarios as well, showing that the total cost of outages (priced at VOLL) is lower than the cost of the strategic reserve on average.

4.6.8 Limitations

We only investigated domestic effects and cross-border effects that directly impact Switzerland (import dependency and trade deficit). However, other cross-border effects are feasible, as other studies have shown for similar policies (e.g. Bhagwat, Richstein, Chappin, Iychettira, & de Vries, 2017; Cepeda & Finon, 2011). In interconnected power systems, the benefits of a strategic energy reserve can spill over to the neighboring systems, stabilizing their grid while they do not pay for the reserve. Furthermore, since the strike price effectively serves as a price cap, it can distort price and investment signals. Internationally operating firms can decide to construct power plants, especially those that rely on scarcity rent for profitability, in adjacent countries where the price is not capped. However, the policy might also incentivize domestic storage capacity investments as it can generate additional revenues for storage operators. Because of these price and investment signals, it is also feasible investment incentives for interconnectors are affected. Further research should look at the impact of a strategic energy reserve on such (cross-border) investment signals and spillover effects.

We chose not to look at investments into batteries or hydropower plants, even though these technologies are likely most affected by the strategic energy reserve policy. The potential of hydropower is already almost fully utilized in Switzerland, there is a relatively small amount of reservoir hydropower that can feasibly be built (SFOE,

2012) and including market-based investments would not have been realistic. Investments into large-scale batteries would also highly unrealistic because their policy environment, market potential, and future investment and operating costs are highly uncertain and subject to change. Nonetheless, further research should investigate how a strategic energy reserve policy would change the investment incentives in these technologies.

Another potential consequence of a strategic energy reserve that we did not look at is the exercise of market power. In our model, all power plant owners are required to bid all of their available capacity. Strategic withholding of capacity by firms could trigger the strategic energy reserve and increase prices for all other power plants that the firm owns. While this risk exists in all electricity markets, the presence of a strategic energy reserve can increase the number of hours with high prices and makes it easier to trigger them, giving a higher incentive to firms to withhold capacity.

Lastly, this study is not a generation adequacy study for Switzerland's power grid and should not be interpreted as such. It would be important to look at many more factors than included in this study to determine whether an electricity system is adequate and to determine the risk of supply shortages. Furthermore, such a study cannot be conducted in isolation for Switzerland and would have to look at the interconnected European grid. This study has looked only at how a strategic reserve would be able to reduce potential supply shortages, and how such a policy would impact the electricity market conditions in Switzerland. The strategic energy reserve has the potential to be more effective and less costly if the dimensions of the reserve are coupled and made conditional on short-term generation adequacy assessments. This could eliminate the costs of operating a (large) reserve in those years where it is not strictly necessary to do so.

4.7 Conclusions

This study has explored the effectiveness of a strategic energy reserve to increase security of supply for the Swiss energy system during the energy transition. The ongoing Swiss energy transition is characterized by a nuclear phase-out and simultaneous promotion of energy efficiency and renewable energy sources such as solar and wind. While the characteristics of the Swiss power system, such as a high interconnection and a large share of hydropower, are relatively unique, the energy transition is similar to other countries that promote renewables and plan on phasing out conventional baseload power plants, whether coal or nuclear. Further advances in energy storage technologies might make strategic energy reserves a possible policy for other countries as well.

The results show that a strategic energy reserve contributes to short-term security of supply as it is able to decrease the risk of supply shortages in winter in Switzerland. Especially when a large number of intermittent renewable power sources is introduced into the electricity system, the availability of flexible hydropower assets in winter contributes to security of supply and the strategic energy reserve can ensure the last-resort availability of such assets. However, it cannot completely eliminate the risk of outage, as we find some supply shortages even in scenarios with a very large strategic energy reserve. This is because there is an inherent risk that the reserved energy is inaccessible, either because the power plant is already running and cannot increase its production capacity, or because the power plant is in a forced outage. These risks should be minimized by spreading the strategic energy reserve over multiple power plants. We further find that the strategic energy is more frequently dispatched than shortage hours occur in the baseline simulations for all scenarios. This shows that the policy creates scarcity on the market that would not have occurred otherwise. Therefore, the reserve should be made as small as possible to prevent such artificial scarcity.

The results further show that the strategic energy reserve becomes more costly rather than cheaper if it is called on, even though the revenues from selling reserved energy serve to compensate the total cost. This is because of scarcity prices: it will become inherently more attractive for a power plant operator to sell their energy in the market during the scarcity periods, rather than participate in the reserve and only be compensated for operational costs if the energy is called upon. Thus, power plant operators will need a higher compensation for participating in the reserve if scarcity periods are more likely to occur.

Larger strategic reserves further reduce the risk of supply shortages, but with diminishing returns to scale. However, the costs are proportional to the size, which suggests there is an optimal reserve size that finds a trade-off between minimizing the supply risk and policy cost. However, a strategic energy reserve was found to increase the cost of electricity supply to consumers in all scenarios, as any potential outages are less costly than operating the strategic energy reserve. The reserve was modeled with a fixed size and time period, and outages were priced at a relatively low VOLL. A tailored strategic energy reserve based on a forecasted short-term need might cost less and have more merit. Therefore, any strategic energy reserve implementation should be done on an ad-hoc basis, based on a short-term generation adequacy assessment.

We did not find any significant impact on investment incentives. This can partly be explained because we did not model investments into hydropower assets, which are the largest participants of the energy reserve and receive most of the additional revenue. However, the investments in domestic renewables or natural gas are not impacted either, nor is the reliance on imports in the winter period reduced. This shows that the policy does not contribute to long-term security of supply and does not contribute to solving the structural problem of winter import dependency. This further supports the conclusion that a strategic energy reserve should be considered a short-term solution only. Future research on strategic energy reserves should look at cross-border investment and spillover effects in more detail and evaluate the effectiveness of a strategic energy reserve when conditional on a short-term generation adequacy assessment.

4.8 Appendix

Table 4.2: Assumptions for power generation investments.

	Permitting time[1] [years]	Construction time[1] [years]	Technical lifetime[1] [years]	Investment increment[1] [MW]	Operating cost, fixed[1] [$/kW-yr]		Operating cost variable[1] [$/MWh]		Investment cost[1] [$/kW]		Emissions[1] [TC/MWh]
					2018	2035	2018	2035	2018	2035	
Wind	6[2]	3	25	100	8.8	4.7	0	0	1396.9	672.1	0
Solar	0.5	1	30	100	49.3	38.8	0	0	940.5	553.2	0
Gas	3	3	55	250	10.4	10.4	2.7	2.7	1051.5	983.8	0.343

[1] Source: NREL, 2018.

[2] Deviates from data source to better reflect significant wind permitting delays in Switzerland.

Table 4.3: Scenarios and assumptions for various exogenous variables.

Variable	Unit	2018	2035
Carbon price[1]	CHF/TC	11	42
Gas price[2]	$/MWh-e	49.85	70.05
Nuclear price[2]	$/MWh-e	7	7
Italian mean electricity price	€/MWh	60.7[3]	74.2
German mean electricity price	€/MWh	41.7[3]	56.8
French mean electricity price	€/MWh	50.2[3]	64.6
Run-of-river production[1]	GWh/year	16’580	17’533
Hydropower energy inflow[1]	GWh/year	18’672	18’883
Waste energy inflow[4]	GWh/year	2’014	2’014
Annual electricity demand	GWh/year	58’483[4]	-
Exchange rate CHF-€[5]	CHF/€	1.13094	1.13094
Exchange rate CHF-$[5]	CHF/$	0.99139	0.99139

[1] Source: Demiray et al., 2018.

[2] Source: NREL, 2018.

[3] Source: ENTSO-E, n.d..

[4] Source: SFOE, 2018c.

[5] Value observed on December 21st, 2018 and kept constant.

Table 4.4: Assumptions and conditions of initial supply mix.

	Capacity [MW]	Storage capacity [GWh]	Operating cost, fixed[3] [$/kW-yr]	Operating cost[3] [$/MWh]	Technical lifetime [year]	Emissions [TC/MWh]
Nuclear	3333[1]	-	99.2[3]	2	50	0
Reservoir hydro	9181[1]	6668[2]	31.1[3]	6	80	0
Pumped hydro	2938[1]	2134[2]	31.1[3]	6	80	0
Run-of-river	3235[1]	-	113.2[3]	0	80	0
Waste[1]	364[1]	245[4]	109.8[3]	5.5	80	0
Solar	1394[1]	-	14	0	30	0
Wind	60[1]	-	51.3	0	25	0
Other thermal[5]	177[6]	-	10.4	2.7	55	0.343[7]

[1] Source: SFOE, 2018c.

[2] Total of 8800 GWh (SFOE, n.d.) divided between reservoir and pumped hydro based on ratio of installed capacity.

[3] Source: NREL, 2018.

[4] Assumed as the volume of one week of waste inflow.

[5] Aggregated all remaining conventional thermal (SFOE, 2018c) into single type.

[6] De-rated capacity based on annual production in 2017, to account for limited availability.

[7] Assumed equal to NGCC gas power plants (NREL, 2018).

Chapter 5 Conclusion

This chapter concludes the thesis. First, I describe and reflect on the merit and limitations of each study individually (section 5.1). I proceed by offering a summary of the overall contributions of the thesis (5.2), separating the contributions to practice (5.2.2), to academic theory (5.2.3), and to advance research methodology (5.2.1). The last parts of this chapter will offer direction and recommendations for further research (5.3) and some final concluding remarks (5.4).

5.1 Reflections

5.1.1 First essay (Chapter 2)

This study performed an *ex ante* quantitative analysis of a first order policy issue: the timing of the nuclear phase-out in Switzerland. Around the time of the study, a referendum was held on limiting the lifetime of the Swiss nuclear fleet to 45 years of operation, which would have effectively provided a fixed schedule for the phase-out. The initiative was rejected but the impact of the nuclear phase-out timing did not leave the public debate. Questions concerning security of supply and the feasibility of the energy transition in combination with the nuclear phase-out pervaded. My analysis looked at this policy issue in detail but also offered general insight into the Swiss energy transition, providing a starting point for the subsequent essays in this thesis.

The policy issue was analyzed using simulations of a system dynamics model. The formal simulation model was created specifically for this study using a conceptual model based on earlier work. The timing uncertainty was explored with several scenarios of the notice period (the time period before the decommissioning of a nuclear power plant that investors are informed—either 1, 3 or 6 years) and several scenarios of the lifetime of the nuclear power plants (50, 55, or 60 years). In addition to these, the impact of interconnector capacity development and demand growth were also evaluated in light of the nuclear phase-out and the Swiss energy transition in general. The simulations gave us the following key findings:

- The notice period, as a proxy for the timing uncertainty of the nuclear phase-out, did not impact the market development. Investment behavior was not noticeably affected, and therefore the other market indicators remained unaffected as well.
- In contrast, the lifetime of the nuclear power plants had a strong impact on the market development. Longer lifetimes of nuclear power plants reduced the total investments into natural gas power plants and

the probability of supply risks. This, however, was only evident when import capacity development was restricted, indicating imports are the default option the market will pursue to manage the nuclear phase-out.

- A growing import dependency was identified in all scenarios. In those scenarios where the development of interconnector capacity was restricted, the import dependency constituted a supply risk. The development of future electricity demand was shown to play a large part in mediating this supply risk.

The study had several limitations, which I categorize into two groups: model limitations and limitations in the experimental setup. The model limitations are related to the choice of methodology (system dynamics) and the system boundaries. System dynamics relies on stocks and flows and does not generally allow the modeling of discrete individual agents. This precludes the implementation of plant-level details as system dynamics generally aggregates power plants based on their similarities. The consequence of this is that certain phenomena could not be included in the model, such as stochastic power plant outages or economic decisions on existing power plants such as renovation, mothballing, or dismantling. This means the analysis strength with regards to security of supply was limited, as stochastic outages cannot be explored, and the explored lifetimes of the nuclear power plants were not tied to market conditions. The first decision to decommission a Swiss nuclear power plant (Mühleberg) was taken for economic reasons. It will go offline 3 years before the technical operating limit that was implemented in the model and assumed by most other studies (50 years). Another limitation the absence of individual agents introduces is the lack of true competitive dynamics, as investors and firm operators cannot be explicitly modeled to interact. These limitations, stemming directly for the choice of system dynamics as model architecture, were the reason a hybrid model was developed for use in the third essay (Chapter 4).

System boundaries describe what is and what is not included into the model. There are two areas that the model lacks in this regard: demand-side resources and cross-border (European) dynamics. The policy issue at hand was initially identified as a domestic supply issue, and therefore these areas were not dynamically implemented but mostly implemented as exogenous factors. However, much of the discovered impact was mediated by variables related to these areas: demand and import capacity. This became evident in the scenario analysis and warrants further investigation. The relationship with the EU and its impacts on the Swiss electricity sector became the topic of analysis in the second essay of this thesis (Chapter 3), and the demand-side, including demand response, was included in much more detail in the hybrid model of the third essay (Chapter 4).

Besides limitations of the model itself, the experimental setup was also subject to some limitations. First, the impact of subsidized renewables was not isolated. The governmental targets for renewables were assumed to be reached in all scenarios. However, these targets were designed with the nuclear phase-out and the potential supply gap in mind. The timing uncertainty could therefore have been more impactful in case the targets were not guaranteed, as this supply gap might not have been effectively countered. Considering the public support for renewables is constantly questioned by various groups in society, it would have been relevant to explore other levels of renewable support. Second, the analysis did not look at the seasonal distribution of the impact of the scenarios. Considering the impact of the timing uncertainty was negligible on market development, the seasonal distribution most likely would have been as well. However, the growing import dependency and strong impact of the demand and interconnection scenarios most likely would have been seasonally differentiated.

Despite these limitations, the study conclusions are important for practitioners and pointed to further research on the Swiss energy transition, providing the starting point for this thesis. The findings contrasted the unimportance of the timing uncertainty and the importance of the schedule of the nuclear phase-out, showing that the chosen transition path, that of a gradual nuclear phase-out, was justified. Additionally, the analysis identified a reliance on imports for security of supply, an area for further research as the analysis in this study was not focused on such cross-border effects. Lastly, the formalization of the model highlighted some issues with the application of a pure system dynamics methodology to electricity systems in transition, which future modeling exercises will have to find a way to deal with more adequately.

5.1.2 Second essay (Chapter 3)

The second essay continues from the first study by placing the Swiss relationship with the EU in the field of energy as the focus of the analysis. The first essay identified a growing reliance on the European electricity system as a result of the nuclear phase-out and energy transition. Therefore, the development of Swiss-EU energy relations is crucial for the Swiss energy transition. However, the overall relationship with the EU has become strained. A bilateral electricity agreement with the EU has not yet materialized, driving Switzerland to the margins in the European electricity sector. The essay explored how this situation has developed in order to gain insight on possible future impacts on Swiss energy policy and governance.

This essay stands out from the other two studies as it is an *ex post* analysis of a third level policy issue, and the method applied is purely qualitative, in contrast to the other two studies which are *ex ante* analyses of lower level policy issues using a quantitative methodology. Furthermore, it looks at governance modes and the policy process rather than a single policy instrument. The choice for a qualitative methodology follows directly from this topic: many of the influencing factors and impacts are socio-political in nature and not (sufficiently) evident in quantitative analysis. The study therefore relies on an in-depth case analysis, using interviews with key stakeholders and a variety of documentary sources to reconstruct the historical developments of Swiss-EU energy governance and policy. A theoretical framework on external governance is then used for analyzing this history, in order to identify possible future developments. There are several key findings in the study:

- Network governance has been and is still the dominant mode of governance in the European electricity sector, but there is a visible trend of increasing hierarchy, especially in the relationship with Switzerland, leaving less room for Switzerland to negotiate exceptions.

- Swiss and EU energy policy have increasingly diverged since the 3rd EU Energy Package. Switzerland has slowly seen its influence in the European energy governance sphere decrease due to gradual EU harmonization and several key events. In recent years, this has led to reduced market access as well.
- Market pressure has been an important motivating factor for Switzerland to adopt EU-compatible electricity legislation in the past, with or without EU coordination. However, Switzerland's future divergence or integration from EU energy policy will more likely depend on the development of general EU-Swiss relations than electricity sectoral dynamics.

The results tell us that the future of Swiss-EU energy relations remains highly politically uncertain. This has implications for energy policy in Switzerland, which has to take into account scenarios of further divergence as well as integration. An important part for a successful energy transition in Switzerland is guaranteeing security of supply while the transition is ongoing, and Swiss-EU relations touch exactly on that.

The study has several limitations. First is the use of interviews as a source of information. Although effort was put into avoiding bias by triangulating the information obtained in the interviews with other sources and balancing Swiss and non-Swiss perspectives, it is impossible to fully rule out. The structure of the paper allows the reader to form their own perspective and provides transparency on how the article reaches its conclusions, by first objectively describing the case (sections 3.4 and 3.5) before going into the analysis with the theoretical framework (section 3.6). This structure further facilitates additional research by presenting a clear objective case description free from analysis, so that other frameworks and types of analyses could be applied.

This introduces the second limitation of the study: the choice of theoretical framework. The external governance framework proved useful as a descriptive lens to identify trends and issues. Furthermore, the case analysis was able to improve the theoretical understanding of the various modes of EU external governance, contributing to the field in general. However, as a descriptive framework, it offers little direct policy recommendations and is therefore of less practical relevance to policymakers, serving only to inform and not to guide towards any particular action. Nonetheless, several policy-relevant conclusions could be drawn from the essay's analysis.

This study dived deeper into a crucial element for the success of the Swiss energy transition: EU relations. It clearly identified the uncertainties, risks, and opportunities of future Swiss-EU relations, including those connected to the negotiations of a Swiss-EU bilateral electricity agreement. While the situation is unlikely to get resolved soon, the Swiss government will have to continue building resilience for the electricity sector in order to deal with this economic and political uncertainty. One of the proposed measures in this context, a Swiss strategic energy reserve, is analyzed in the third essay.

5.1.3 Third essay (Chapter 4)

This essay continued on the first two essays by analyzing the effectiveness of a strategic energy reserve as a policy instrument meant to increasing security of supply during the Swiss energy transition. One of the main rationales for this strategic energy reserve is the potential supply risk from growing more dependent upon electricity imports and can therefore be seen as a direct consequence of the nuclear phase-out and the politically uncertain Swiss-EU energy relations, the topics of the first and second essays.

The Swiss situation is relatively unique. However, a strategic energy reserve could feasibly be considered in other countries undergoing a similar transition path—phasing out year-round baseload power sources in favor of seasonal renewables—if their energy storage capacity develops further and the policy is proven successful in Switzerland. The practical and academic relevance of this study therefore extends beyond the Swiss case alone by providing a first academic analysis of this novel policy instrument.

The essay analyzes the introduction of a new policy instrument in Switzerland; a second order policy change. However, the analysis also evaluates the policy settings, or design parameters, which are first level policy changes. No strategic energy reserve has been implemented in another country, so *ex ante* analysis through quantitative simulation is one of the few possibilities to generate insights about its potential impacts. The system dynamics model of the first study provided the starting point for the simulation model in this study. However, the limitations of the system dynamics model (as described in section 5.1.1) had to be overcome as they would have been prohibitive to analyze the strategic energy reserve. In order to overcome these limitations, a hybrid modeling paradigm was chosen. A hybrid model incorporating elements from agent-based modeling is able to include plant-level and agent-level details, one of the main elements lacking from the system dynamics model. This allowed the implementation of crucial phenomena in the new model that were not possible before, such as stochastic plant outages, flexible demand-side resources, plant-level economic decisions, and competitive dynamics between investors, while preserving the system perspective of the original model. However, because the hybrid modeling paradigm fundamentally changed the way the model works, the model had to be entirely rebuilt. The conceptual model of the first study (Appendix A, p. 125) provided the starting point, but the formalization (the set of equations) of the hybrid model had to be completely rewritten (Appendix D, p. 182).

Not only were most of the modeling limitations of the first study overcome in the new hybrid model iteration, other parts of the model were also improved based on the findings of the first and second study. For instance, the lessons on Swiss-EU relations from the second study were taken into account in order to model the international trading conditions, loop flows, and interconnector capacity more adequately. Because the political uncertainty about Swiss-EU energy relations made it difficult to simulate the future development of the relationship, the decision was made to extrapolate the current situation into the future, rather than aggravate or alleviate the issues. This made the analysis relevant for policy decisions today, as these are made in the context of the current political situation. The third essay further improved on the first essay by isolating the impact of subsidized renewables and evaluating at the seasonal distribution of the impact as well, both of which are important but were not done in the first study. All these improvements led to an overall more flexible model and a more robust analysis. There are several key takeaways from the analysis:

- A strategic energy reserve can provide a solution to resolve a short-term winter security of supply issue but cannot completely resolve the supply risk. It does not improve long-term security of supply, as it does not structurally improve the situation causing the supply problems, either by promoting domestic investments or reducing the import dependency in critical periods.
- The strategic energy reserve was shown to create scarcity on the market that would not have occurred otherwise. This can lead to slight overall increase in market prices; however, this effect is small even for a large reserve.
- The strategic energy reserve was not a cost-effective way of reducing the risk for shortages, as the total consumer costs (which include the outage costs) were found to always be higher with the policy in place than without. Overall, the reserve was shown to be more costly when it is most needed, as the increased prevalence of scarcity prices associated with a higher supply risk provides an incentive not to participate. Consequently, the operators need to be compensated more in order for them to participate.
- The total reserve cost increases linearly with the reserve size, but the benefit of reducing the supply risk shows diminishing returns to scale. A higher strike price is more effective at reducing the supply risk.
- Using a hybrid agent-based system dynamics model was shown to be successful and a strong improvement over a pure system dynamics or agent-based model in the context of socio-technical transitions of electricity systems. No fundamental limitations were identified with the modeling methodology, showing the flexibility of the hybrid model approach.

The analysis and findings are not without their limitations. Many of the limitations of the study were already explicitly discussed in the study in section 4.6.8 (p. 89). Most of these focus on the elements that the analysis did not take into account, such as some types of cross-border effects and market power, the limited investment portfolio and limited assessment of the generation adequacy. Especially the last two can be considered consequential. First, there is likely a potential for reducing the costs and increasing the effectiveness of the strategic energy reserve, if the implementation is tied to a short-term generation adequacy study. The analysis did not explore such dynamic implementation. Second, the limited investment portfolio meant that the investment incentives for hydropower plants were not investigated, even though these are likely the most affected by the policy. These limitations could change some of the main insights, especially that domestic investment incentives are unaffected or that the reserve is not cost-effective.

Despite these limitations, the practical implications of the findings are clear. While the short-term benefit of a strategic energy reserve was clearly shown, there are some potential risks and inefficiencies that policymakers and regulators will have to take into account. The benefits only arise if there is an actual supply risk, and in the business as usual scenario there was none. The implementation should thus be accompanied by a comprehensive generation adequacy assessment to assess the need for the policy. If not, it essentially serves as a type of subsidy for storage operators, especially hydropower. The potential for reducing costs and increasing efficiency of a tailored strategic energy reserve needs to be investigated, including a comprehensive cost-benefit analysis to find out whether the policy is cost effective at preventing outages or not. Future research on the strategic energy reserve should also look at the factors omitted in this study, such as market power, cross-border investment incentives, and other spill-over effects.

5.2 Contributions

5.2.1 Methodology

This thesis contributes to advance research methodology in several ways, notably in relation to the modeling and simulation of the first and third essay. First, the thesis contributed to the field of modeling as a methodology for policy analysis during sustainability transitions. Some argue that modeling has the tendency to excessively reduce the complexity involved in transitions (McDowall & Geels, 2017), but most researchers and the overall research community[14] have repeatedly stated the value and potential of modeling as a methodology in sustainability transitions studies (Köhler et al., 2019). Nonetheless, simulation and modeling remain a minor methodology, used by a small fraction of studies within the research field[15]. This thesis proved the value of modeling as a methodology. Especially the use of modeling to analyze first and second order policy issues is novel in the field of energy transitions, as studies in this field more commonly look at third order policy changes and tend to neglect the other two levels. Furthermore, the modeling studies within the sustainability transitions field generally focus on modeling transitions pathways, while the actual first and second order policies involved and their effect on the transition are not analyzed in detail. Inclusion of policy analysis into the studies of sustainability transitions facilitates research that is directly relevant for policy decisions, as demonstrated by this thesis.

Second, the conceptualization of the Swiss electricity market can serve as a starting point for other researchers modeling a similar system. The conceptual model contains two important elements. The first is the hybrid model architecture design which specifies how agent-based modeling and system dynamics can be successfully combined to create an integrated hybrid model, rather than the more commonly seen sequential or interfaced approaches to hybrid models (Swinerd and McNaught, 2014). Despite increasing attention in the area, there is overall a lack of guidance to hybrid modelers on how to combine different modeling paradigms. The conceptualization of the hybrid model in the third study (section 4.4, p. 72) can help other researchers attempting a similar hybrid approach. The second important element is providing instructions on how to integrate a long-term market model with a short-term market and dispatching model. Swinerd and McNaught remark that “the effective and efficient representation of different scales of a system and the coupling between them is perhaps one of the biggest challenges to single paradigm models” (2014, p. 232). Most studies opt either for a long-term perspective or a short-

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[14] The Sustainability Transitions Research Network (STRN) emphasized the need to further explore modeling as a methodology for transition research in both their 2010 and 2019 Research Agenda (Köhler et al., 2019; STRN, 2010).

[15] Only about 5% of all papers on energy or sustainability transitions on Scopus contain the keyword “modeling” or “simulation”.

term perspective, and then approximate the other scale, if at all. An example would be the use of “representative days” in long-term power system analysis. The models in this thesis, however, combine a full implementation of a short-term (hourly) market and plant dispatch dynamics as well as long-term market dynamics containing various types of economic decisions such as investments and renovations. This is a combination that is necessary and especially interesting for modelers that look at how long-term market developments (including transitions) impact short-term market dynamics or vice versa.

Other elements of the conceptual model are valuable for modelers as well. Electricity market models, regardless of the type of modeling, generally use marginal costs for setting the supply bids and making dispatching decisions. This is an acceptable approach as long as the majority of power generation in the market has either unhindered access to purchase fuel (generally assumed for fossil and nuclear fuels), or no possibility of storing energy and availability is based on external factors (e.g. sun, wind). In most countries, this is still the case for the majority of the fleet and using a marginal-cost based approach is therefore not overly limiting. However, in countries with significant share of hydropower, such as Switzerland, Austria, Norway, etc., this approach will not deliver adequate results. Furthermore, energy storage is expected to develop further in other countries as well, for instance through batteries or some other form of storage (heat, pressure, gravity, chemical, etc.). Renewables that are currently intermittent will become dispatchable, but their supply of energy will remain limited. Thus, opportunity costs will become important in future electricity markets as the energy transition progresses, because their operators will offer their electricity not when directly available, but when the market prices are highest. There will then be a premium on top of the marginal costs—opportunity cost—that the operators will use to bid in the market (see Equation 4.1, p. 74) and thus determines which power plants get dispatched when, changing the market behavior. The conceptualization and the formalization of opportunity cost bidding created in this thesis is flexible and technology neutral and can readily be implemented by researchers. The strategic energy reserve algorithm created in this thesis makes a similar contribution. As the policy has not been implemented in any country, there was no other published research implementing the policy in a simulation model. The conceptualization and formalization had to be developed from scratch, and the version described in this thesis can be implemented by other researchers in their models.

Lastly, this thesis showed the value of hybrid designs in modeling. While some researchers argue that mixed-method or hybrid model designs should be used sequentially rather than in an integrated design, in order to be able to focus on each individual paradigm’s strengths (Geels, Berkhout, & van Vuuren, 2016), others have stressed the benefits of integrated approaches (Swinerd & McNaught, 2014). These researchers agree however that further research is required comparing the benefit of using a hybrid design compared to a single modeling paradigm. This thesis modeled the Swiss electricity system using a single modeling paradigm in the first essay and an integrated hybrid design in the third essay. Both models were based on the same conceptualization and are therefore relatively comparable. The hybrid ABM-SD model offered obvious advantages over the single paradigm SD model. Many of the limitations of the SD model were overcome by the specific addition of the agent-based perspective and the hybrid model offered more flexibility in modeling choices. This thesis therefore supports the added value of using an integrated hybrid modeling approach over a single modeling paradigm, at least in the case of socio-technical transitions and electricity markets.

5.2.2 Practice

This thesis delivered several contributions that are directly relevant for policy makers and practitioners in the electricity sector. Policymakers can use the findings and recommendations of each separate study to inform their policy decisions. Firms in the electricity sector can also find interest in the findings, as they detail the impact of energy policy and governance decisions on the sector in which they operate. These will impact their business and therefore they can use the findings to inform their strategic decisions. Although the substantive contributions are already detailed in each study separately, this section offers a brief summary, placing all recommendations and findings in a single context.

The Fukushima disaster and subsequent nuclear phase-out provided a clear impetus for governmental planning of the energy transition. While the phase-out timing can be left uncertain without any impact on the energy transition or the electricity market conditions, the lifetime of the nuclear power plants will have strong impact on both. Extending their operation can reduce the risk of supply shortages and price increases. However, other factors should be taken into account when taking this decision, as this study only looked at the impact on security of supply and domestic investments, but not the economic viability or environmental safety of extending the nuclear operations. The nuclear phase-out will likely increase the dependency on imports, especially in winter. The relationship with the EU has been important for security of supply and will become more so because of the energy transition. However, the relationship with the EU has become strained, leading to a loss of influence in legislative processes and deteriorating market access for Switzerland. The future of Swiss-EU relations is politically uncertain, and the room for negotiating exceptions has diminished due to the overall harmonization of the EU electricity markets and several key events in Swiss-EU relations. The ongoing negotiations for an electricity agreement present both a risk and opportunity. The risk lies in further deepening the hierarchical EU external governance processes that have been developing with Switzerland, while the opportunity lies in reintegration to EU network agencies and legislative processes, providing influence and better market access for Switzerland. EU energy legislation will directly and indirectly impact the Swiss electricity sector, even without an agreement. A strategic energy reserve can alleviate a part of the short-term supply risk in the winter period, should it arise, but cannot remove such a risk altogether. Different or additional policies will be needed to manage the energy transition and the risks to security of supply, should they materialize after the nuclear phase-out. The policy is likely not cost-effective and comes with several other downsides, such as increasing consumer costs, power prices, and inducing artificial scarcity periods. Furthermore, the strategic reserve does not contribute to solving the structural causes of the security of supply risks, only to treating the symptoms. A larger strategic energy reserve will be more effective, but there are diminishing returns to scale while the costs grow linearly. Therefore, an optimum size should be found minimizing costs and maximizing benefits. The strategic energy reserve should further have a high strike price to increase its effectiveness. The potential for a dynamic implementation based on short-term generation adequacy assessments should be investigated, as this could increase the benefits while reducing the overall costs.

5.2.3 Theory

This thesis' main contributions were to methodology and practice; however, several contributions of this thesis are important to academic theory as well. They can be divided into contributions to sustainability transitions and external governance. The three essays together form a coherent case study on the Swiss energy transition and can serve as a basis for further academic analysis, especially the historical analysis of Swiss-EU energy relations in the second study.

5.2.3.1 Sustainability transitions

As described at the start of the thesis (section 1.1.1), one of the main strains of research in transitions studies is the multi-level perspective or MLP, which has led to the focus on transition pathways. This thesis combined three essays on the Swiss energy transition in a single narrative and this allows for a theoretical reflection using the Swiss energy transition as a single case in the context of these pathways. Does the research in this thesis support the multi-level perspective and transition pathways, or contradict it, and in case of the former, as what type of transition pathway can the Swiss transition be characterized?

Adopting a multi-level perspective, the Swiss electricity regime can be seen as changing from the niche level, with new (global) innovations such as solar gradually developing, as well as from the landscape level, through social and political pressure. Social pressure against nuclear power had been slowly building for decades from environmental groups but had never been able to push through a phase-out, as evidenced by the large number of failed referenda. Similarly, renewable energy innovations were developing on a global scale, and international collaboration to fight climate change was slowly mounting as well. The Fukushima disaster in Japan created a window of opportunity where the selection pressures came together and the nuclear phase-out could be pushed through, in favor of renewable energy. However, this was merely the political decision and the actual transition is a longer, more gradual process. These developments are clear signs of a *purposive transition* in Smith et al.'s typology of transition contexts (see Figure 1.3, p. 28), where major decisions and coordination efforts are taken by the government and its various levels. Smith et al. speak of purposive transitions when the resources to respond to the selection pressures are developed externally to the incumbent regime, and the level of regime coordination responding to the selection pressures is high (2005, p. 1502). In Geels and Schot's typology of socio-technical transition pathways (2007), however, the Swiss transition does not clearly resemble a single ideal archetype pathway, showing characteristics of both the *reconfiguration* as well as the *substitution* pathway. In the reconfiguration pathway, 'symbiotic' niches are integrated into the incumbent regime, and the regime will adjust to incorporate these niches over time. This is clearly visible with the slow and gradual update of renewable energy in Switzerland, where the traditional players, often regulated monopolies, are integrating these technologies alongside their traditional offering. A policy such as the strategic energy reserve can be seen as a coping mechanism of the incumbent regime. In the substitution pathway, an external shock, such as the Fukushima nuclear disaster, allows for a relatively developed technological niche to take advantage of the window of opportunity to “break through” and replace the incumbent regime. This resembles the way renewables have managed to replace nuclear power in the country’s future electricity system.

While a single case study does not have the generalizability to confirm the validity of such broad theories, the above discussion adds to the existing body of case studies in favor of the multi-level perspective and transition pathways as analytical heuristics to study energy transitions.

5.2.3.2 External governance

External governance is a branch of political science that has its roots in traditional governance studies. Rather than explore the dynamics of internal governance processes, external governance explores how governance processes extend beyond the borders of the governor’s formal legal authority. This lends itself especially well in the context of the EU associating with third countries, as shown in the second study (Chapter 3). Our analysis tested the power-based hypotheses concerning modes of external governance originally postulated by Lavenex and Schimmelfennig. According to these hypotheses, “the modes of external governance do not correspond to EU internal structures but to external structures of power and interdependence” with regard to third countries (2009, p. 803). High and asymmetric interdependence (skewed in the EU’s favor) should favor hierarchical governance. High, symmetric interdependence should favor market governance, shown by strong market integration without a dominant governance provider. Network governance should then arrive in situations of medium interdependence and can occur in both symmetrical and asymmetrical power relations. For network and hierarchical governance, these hypotheses seem consistent with the observations on Swiss-EU relations made in the second study. Interdependence of the European electricity markets (including Switzerland) has grown continuously over the last few decades, both physically and economically, and as a result, pure network solutions were no longer deemed sufficient or optimal, leading the EU to introduce governance processes that were more hierarchical in nature. Market governance processes have also played a role in Swiss adaptation to EU energy policy, as described in section 3.6.2 (p. 63), but those situations have consistently been asymmetrical, in conflict with the hypothesis of Lavenex and Schimmelfennig.

While a single case as presented in this thesis does not offer the generalizability to challenge a theory, it at least suggests the theory of external governance should be further refined to accommodate these different instances of market governance, where asymmetric interdependence as well as symmetric interdependence are possible.

5.3 Outlook on future research

The thesis provides a furtive ground for future research. The section below separates the various lines of research that can be followed from this thesis. First, the outlook on future research for modeling in transitions research is described in relation to the work done in this thesis. Second, the outlook for further research possibilities related to the strategic energy reserve are described.

5.3.1 Modeling socio-technical transitions

In terms of modeling electricity systems undergoing a socio-technical transition, the thesis provides several avenues for future research. Some have already been discussed as modeling limitations encountered in this thesis, as discussed in sections 4.6.8 (p. 89) and 5.1.3 (p. 96). Overcoming these limitations presents an obvious future research opportunity and this section will therefore not repeat them. Rather, the section below discusses several promising areas of research in model development in relation to transitions and electricity systems that have not yet been discussed in detail.

This thesis contrasted a single paradigm model in the first study with a hybrid paradigm model in the third study. Clear benefits were identified as a result from moving towards a hybrid modeling paradigm. The move allowed the retention of the basic conceptual model of the system dynamics model while adding agent-level details, providing a high level of modeling flexibility. However, the comparison between hybrid and single paradigm is not perfect in this thesis. The modeled subject was the same, but the units of analysis were different. Furthermore, no comparison with a single paradigm agent-based model was done to complete the comparison SD versus hybrid SD-ABM versus ABM. The benefits of hybrid modeling found in this thesis are therefore not fully generalizable. More research is needed on the advantages and disadvantages of hybrid versus single paradigm modeling.

Policy emergence is another promising line of future research. The policy process, or how policies are designed and implemented, is generally implemented as an exogenous (external) process in simulation modeling. The policy process in this thesis was exogenous as well, meaning the policies were introduced and dimensioned by me, to be able to observe its impact on the modeled system. This is a suitable method for policy analysis as it supports policy decision making in the present. However, including the policy process into the model endogenously could benefit the exploration of transition dynamics from an academic standpoint. Indeed, many strains of transition research, for example transition management (see section 1.1.1, p. 26), advocate routine adjustment of steering policies, systematically triggering policy reviews when new industries and technologies develop, or new information arrives. Treating the policy process as exogenous makes it impossible to explore such transition dynamics in more depth. Endogenous policy emergence could lead to important insights in relation to the so-far mostly qualitative transition theories. Transition theories are generally based on qualitative case studies performed *ex post* and have not been used much for quantitative *ex ante* analyses. Endogenously modeling policy emergence could bridge that gap.

Another promising avenue for future research is the demand side of the electricity market. The models in this thesis were still principally focused on supply side, as is the traditional approach in electricity market modeling. Supply-side dynamics are often modeled more elaborately compared to demand-side dynamics. However, the demand side is becoming more and more important and therefore such a supply-focused approach to simulation models is no longer sufficient. In comparison to the SD model, the hybrid model already integrated the demand side more elaborately, including explicit inclusion of demand response, opportunity cost bidding for storage demand, and somewhat flexible consumer load. However, further improvements can be made on granularity and variety of consumer demand decisions, price elasticity, demand response, etc. This would allow the exploration of policies in relation to consumption behavior tied to the use of electric mobility or heat pumps, for instance, and in reverse their systemic effect on the market.

Lastly, batteries are a promising future improvement of electricity market modeling. The implementation of energy storage assets in the hybrid model was relatively simple, only allowing electricity arbitrage as mode of operation. Furthermore, their regulatory environment is not looked at other than the strategic energy reserve. Technological variety is important to include, as well as the ability to distinguish different behavioral patterns and scales. This will allow variety in the way batteries are operated, rather than treating them all as the same, and would likely more accurately reflect the situation in the coming years. The various policy environments for batteries could and should be investigated, as batteries have potential to contribute to the energy transition by for instance stabilizing the grid and smoothing demand and supply mismatches. Batteries could potentially be used for many different business cases, such as frequency or voltage control, balancing, arbitrage, facilitating local or self-consumption, etc. Many of these services are highly regulated, and the policy environment allowing or prohibiting these services will be an important determinant in the future development of batteries and their contribution to the energy transition. All these elements need to be considered in future electricity markets and policies, and therefore present great opportunities for simulation model development and energy policy research in general.

5.3.2 Strategic energy reserve

The exploration of the strategic energy reserve in this thesis provided a start, but several questions remain that could be tackled in future research. Some potential avenues for future research were already identified in the chapter itself (section 4.6.8, p. 89), but this section will build on that.

The thesis only explored a basic implementation of a strategic energy reserve, but many different design types are possible. For instance, the energy reserve could include a minimum available capacity requirement, bringing the policy closer to a strategic capacity reserve in function. The implementation could be done dynamically, based on forecasted need, which could potentially increase the policy effectiveness while minimizing the cost. The energy could be released in several steps throughout the covered scarcity period, to avoid flooding the market at a single moment. The participation eligibility criteria could be explored, including the objective technical potential for allowing foreign operators to participate in the reserve. Considering the policy has not been finalized in Switzerland, the final version might not look the same as the one explored in this thesis.

Additionally, future research should focus on the cross-border impact of strategic energy reserves, as has been done for instance for capacity mechanisms (e.g. Bhagwat et al., 2017; Cepeda & Finon, 2011; Hasani & Hosseini, 2011). The strike price of the energy reserve effectively serves as a price cap that can potentially change market prices in one country. This can spill-over into neighboring countries by changing investment incentives for power plants or interconnector capacity. Furthermore, a neighboring country might benefit from the stabilizing effect of the reserve without their consumers paying for it. Other positive and negative spill-overs are feasible and should be looked at in the context of the European power grid, not only the Swiss power grid.

Lastly, hydropower investment incentives were largely left out in the analysis, even though hydropower is most likely the largest recipient of the financial compensation of the energy reserve. The impact of the strategic energy reserve on the hydropower operators’ financial situation should be investigated, and whether it provides any incentive for upgrading old facilities or building new facilities that could contribute to furthering long-term security of supply.

5.4 Concluding remarks

This thesis analyzed three energy policy issues for the Swiss energy transition in detail, and by doing so made methodological and theoretical contributions in the fields of sustainability transitions, external governance, and simulation modeling, as well practical contributions to the governance of the Swiss energy transition. Throughout the thesis, I have tried to analyze each policy issue as objectively as possible, providing transparent and detailed written analysis of each research endeavor.

Writing this thesis has been a long but rewarding journey. I have gained an incredible amount of knowledge on energy policy, politics, sustainability transitions, modeling, simulation, and many other subjects. The three essays chosen to become a part of this thesis each represent a specific point in my doctoral research career. The essays in the order as I presented them in this thesis are a testament to the growth I have experienced as a researcher and a person.

António Guterres, Secretary General of the United Nations, has expressed his opinion that “climate change is *the* defining issue of our time, and we are at a defining moment”[16]. There is an urgent need for more research on sustainable energy policies that are practicable and effective. Decisions are being made today and policy makers need good information to make informed decisions. I hope that my research and recommendations will be useful for decision makers in Switzerland and in other places that are looking to accelerate the sustainable energy transition in a fair and secure manner. I hope that my contributions to developing methodologies for policy analysis in this transition context will aid the research of others so that they will be better able to advise policy makers and industry strategists to make sustainable decisions. There is no single solution, silver bullet, or magic wand that will solve the problem overnight. Realizing the sustainable energy transition will not be easy and will involve many steps, mistakes, and revisions, I nonetheless believe it is fully within the scope of our collective ability.

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[16] Guterres has repeated this phrase many times in public since the UN Climate Change Summit in 2018 (Sengupta, 2018).

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Appendices

A. Conceptual electricity market model

This appendix contains a graphic representation of the conceptual model upon which the simulation models in this thesis are based. The conceptual model is split into separate modules that group related model elements together for comprehension purposes. The graphs are a simplification of the model and are intended to aid the reader understand the general way the model works, and the graphs are therefore not a true or complete representations of the variables and equations included. The full set of variables and equations of the SD model and the hybrid ABM-SD model are found in Appendices B and D, respectively.

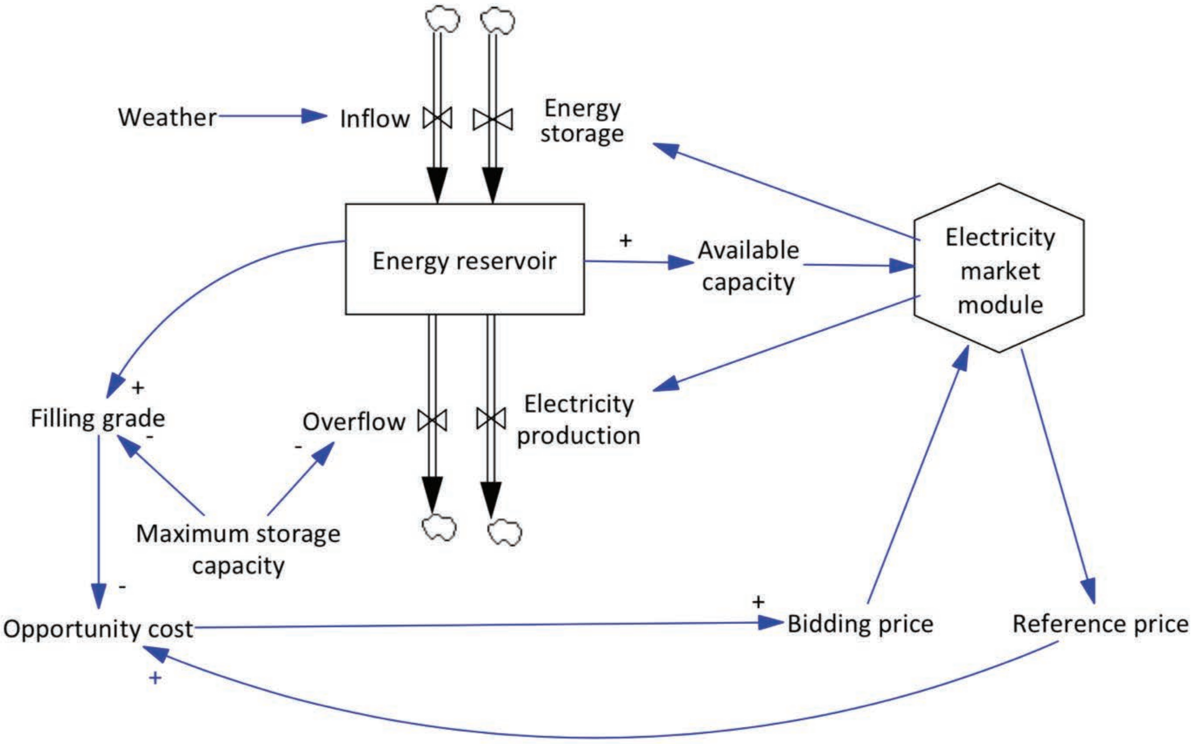

Figure A.1: Conceptual model - energy reservoirs.

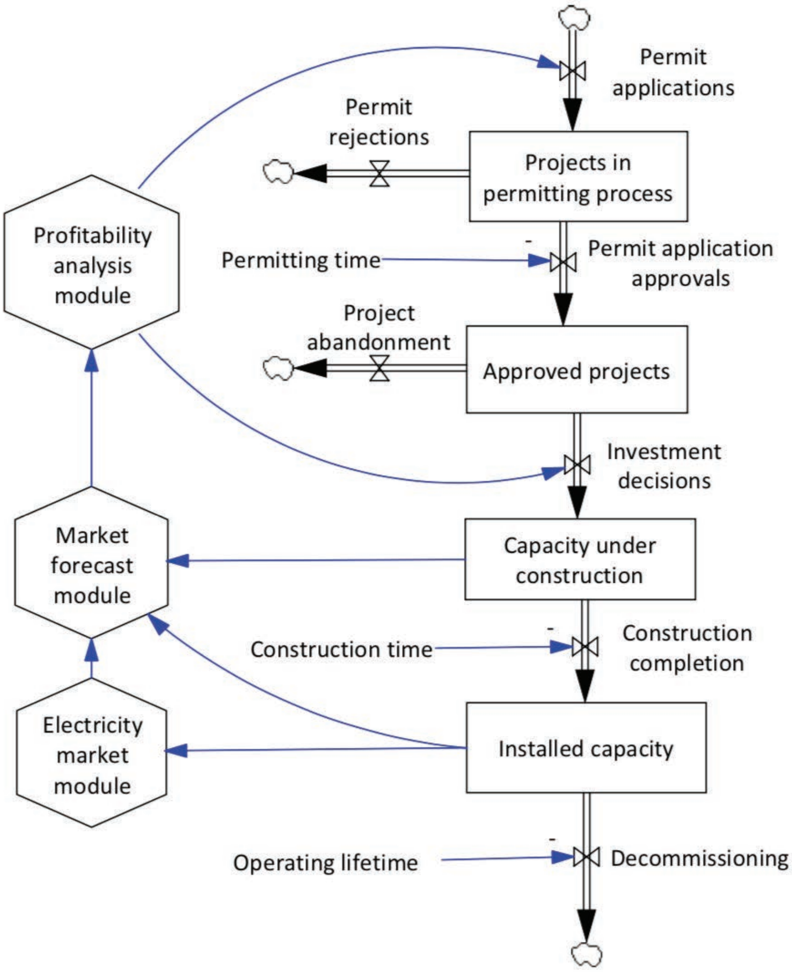

Figure A.2: Conceptual model - installed capacity.

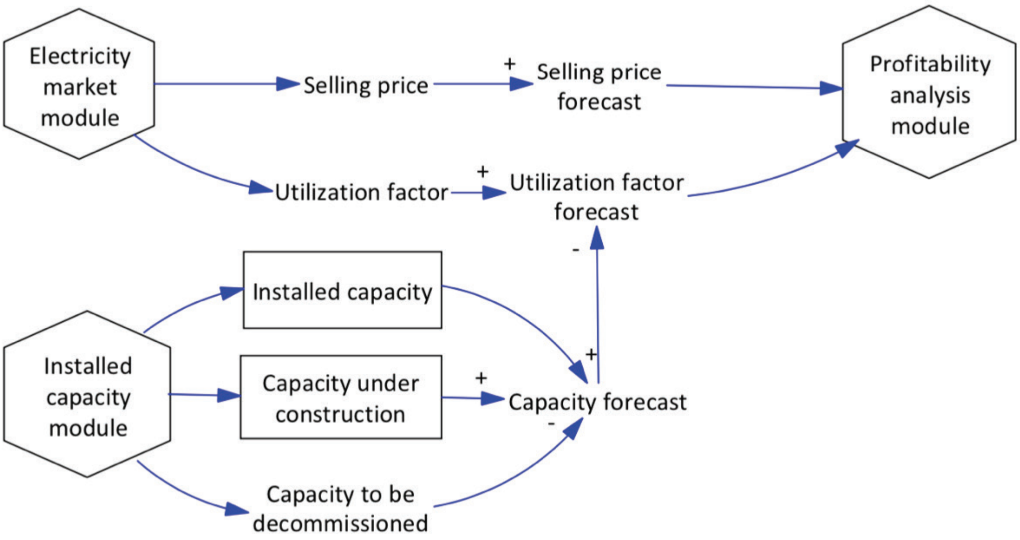

Figure A.3: Conceptual model - market forecast.

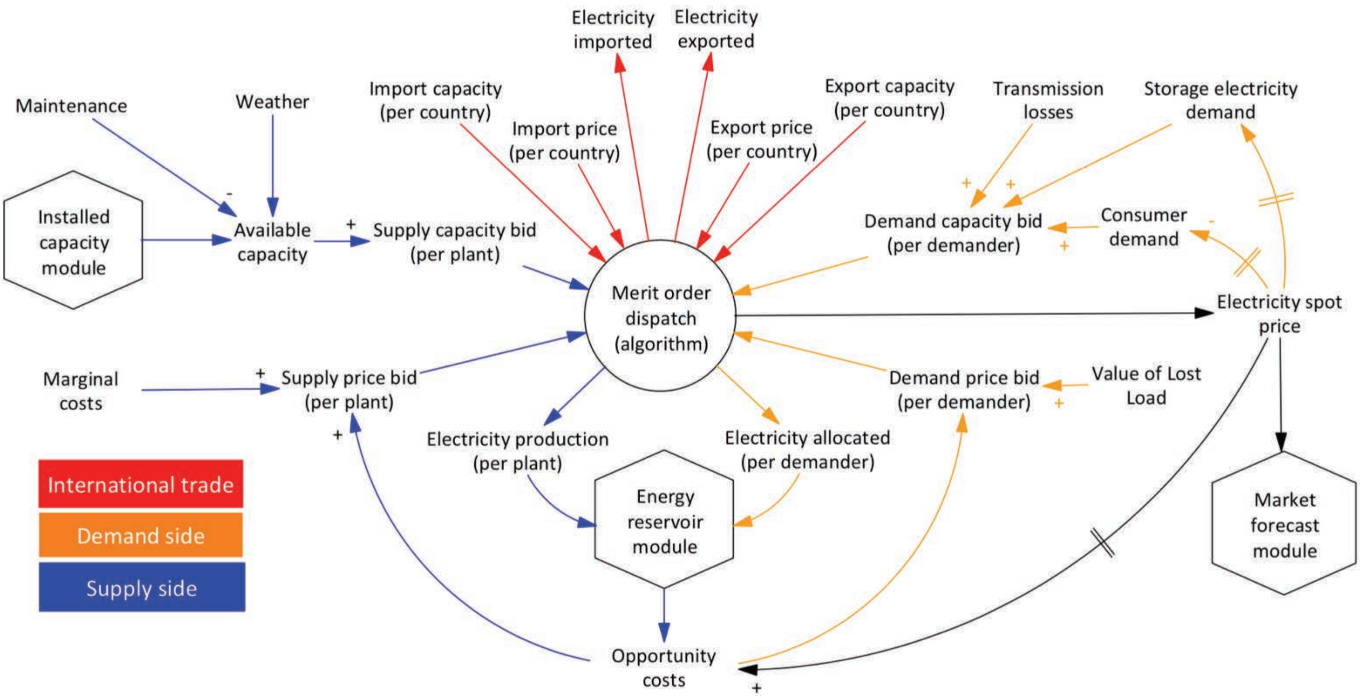

Figure A.4: Conceptual model - electricity market, including supply (blue), demand (orange), and international trade (red).

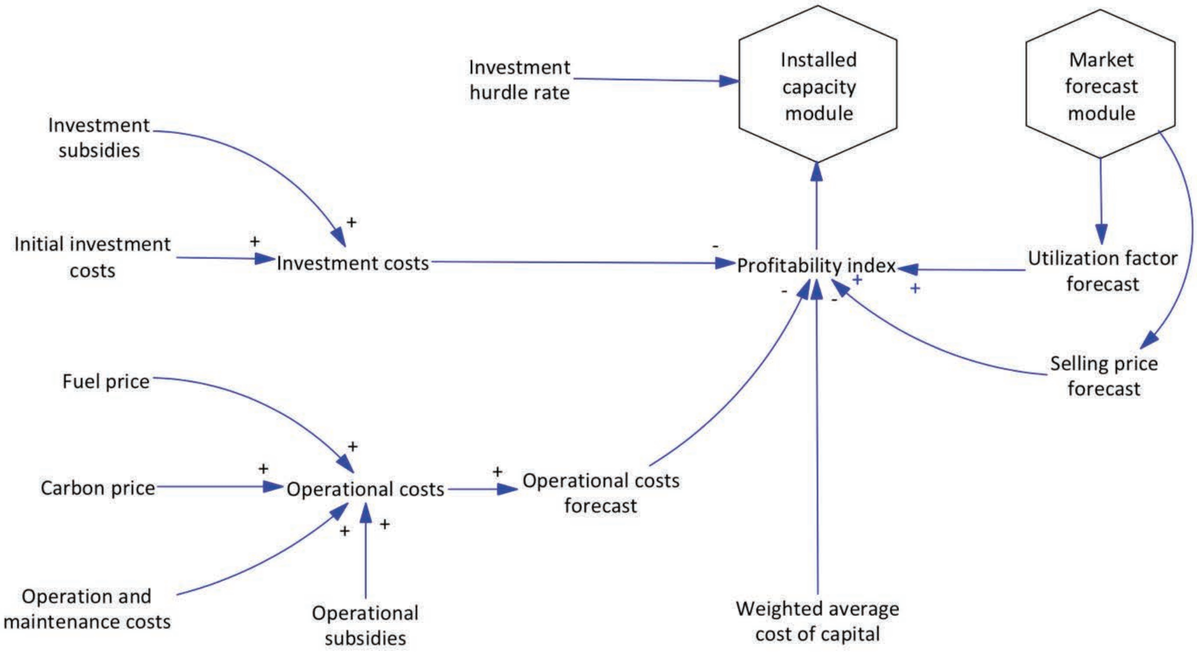

Figure A.5: Conceptual model - profitability analysis.

B. Equations system dynamics transition model.

The system dynamics model used for the study in Chapter 2 (p. 41) was created on the Vensim® DSS for Windows 6.4E software platform. System dynamics is a type of equation-based modeling, meaning that the entire model can be described by the sum of its equations. This appendix contains all variables and their equations in the model, in the following format:

```
Name of variable=
        Equation corresponding to variable
        ~       Unit
        ~       Comment
```

A backslash (\) at the end of any line means the line is interrupted and continues on the next line; the backslash is not part of the equation. Certain variables can have different initial values in different simulations, based on the scenario or policy explored, as described in Chapter 2 (p. 41). In those cases, the default value is put in the variable equation and the range of values used in the different scenarios is described in the comment. The equations are written in the proprietary modeling language of Vensim, which should be easily understood as it is based on natural language and common logical operators (e.g. “IF THEN ELSE”), but an explanation of the language and proprietary equations can be found in the software documentation: https://www.vensim.com/documentation/index.html

Table B.1: Equations system dynamics transition model.

```
CO2 emissions from CCGT=
        (MAX(CCGT production-CCGT installed capacity initial,0))/CCGT firing efficiency*Carbon content per MWh gas
        ~       tCO2/Hour
        ~               |

CO2 counter= INTEG (
        CO2 emissions from CCGT-IF THEN ELSE(Year end=1,CO2 counter*C,0),0)
        ~       tCO2
        ~               |

Nuclear phaseout 3y ahead=
        IF THEN ELSE(Phaseout scenario=1,
        373*IF THEN ELSE(Year=2019:AND:Year end=1,1,0)+
        365*IF THEN ELSE(Year=(MAX(2019-Investor foresight,Start year)):AND:Year end=1,1,0)+
        365*IF THEN ELSE(Year=(MAX(2021-Investor foresight,Start year)):AND:Year end=1,1,0)+
        985*IF THEN ELSE(Year=(MAX(2029-Investor foresight,Start year)):AND:Year end=1,1,0)+
        1190*IF THEN ELSE(Year=(MAX(2034-Investor foresight,Start year)):AND:Year end=1,1,0)
        ,
        IF THEN ELSE(Phaseout scenario=2,
        373*IF THEN ELSE(Year=2019:AND:Year end=1,1,0)+
        365*IF THEN ELSE(Year=(MAX(2024-Investor foresight,Start year)):AND:Year end=1,1,0)+
        365*IF THEN ELSE(Year=(MAX(2026-Investor foresight,Start year)):AND:Year end=1,1,0)+
        985*IF THEN ELSE(Year=(MAX(2034-Investor foresight,Start year)):AND:Year end=1,1,0)+
        1190*IF THEN ELSE(Year=(MAX(2039-Investor foresight,Start year)):AND:Year end=1,1,0)
        ,
        373*IF THEN ELSE(Year=2019:AND:Year end=1,1,0)+
        365*IF THEN ELSE(Year=(MAX(2029-Investor foresight,Start year)):AND:Year end=1,1,0)+
        365*IF THEN ELSE(Year=(MAX(2031-Investor foresight,Start year)):AND:Year end=1,1,0)+
        985*IF THEN ELSE(Year=(MAX(2039-Investor foresight,Start year)):AND:Year end=1,1,0)+
        1190*IF THEN ELSE(Year=(MAX(2044-Investor foresight,Start year)):AND:Year end=1,1,0)\
        ))
        ~       MW/Hour
        ~               |

CCGT installed capacity initial=
        SAMPLE IF TRUE(Time=0,CCGT installed capacity,0)
        ~       MW
        ~               |

CO2 emissions yearly=
        SAMPLE IF TRUE(Year end=1,CO2 counter,0)
        ~       tCO2
```

```
        ~                       |

Start year=
        2015
        ~       year
        ~                       |

Nuclear phaseout=
        IF THEN ELSE(Phaseout scenario=1,
        373*IF THEN ELSE(Year=2019:AND:Year end=1,1,0)+
        365*IF THEN ELSE(Year=2019:AND:Year end=1,1,0)+
        365*IF THEN ELSE(Year=2021:AND:Year end=1,1,0)+
        985*IF THEN ELSE(Year=2029:AND:Year end=1,1,0)+
        1190*IF THEN ELSE(Year=2034:AND:Year end=1,1,0)
        ,
        IF THEN ELSE(Phaseout scenario=2,
        373*IF THEN ELSE(Year=2019:AND:Year end=1,1,0)+
        365*IF THEN ELSE(Year=2024:AND:Year end=1,1,0)+
        365*IF THEN ELSE(Year=2026:AND:Year end=1,1,0)+
        985*IF THEN ELSE(Year=2034:AND:Year end=1,1,0)+
        1190*IF THEN ELSE(Year=2039:AND:Year end=1,1,0)
        ,
        373*IF THEN ELSE(Year=2019:AND:Year end=1,1,0)+
        365*IF THEN ELSE(Year=2029:AND:Year end=1,1,0)+
        365*IF THEN ELSE(Year=2031:AND:Year end=1,1,0)+
        985*IF THEN ELSE(Year=2039:AND:Year end=1,1,0)+
        1190*IF THEN ELSE(Year=2043:AND:Year end=1,1,0)
        ))
        ~       MW/Hour
        ~                       |

Phaseout scenario=
        1
        ~       year
        ~       1 = original ( 50 years)
                2 = new licenses, but early shutdown ( 55 years)
                3 = new licenses ( 60 years)
                Source: World Nuclear Association
        |

Investor foresight=
        6
        ~       year
        ~       Years before shutdown of a power plant investors are informed, suggested: 6 / 3 / 1
        |

Total export NTC=
        DE AT hourly export NTC+FR hourly export NTC+IT hourly export NTC
        ~
        ~                       |

DE AT hourly export NTC=
        IF THEN ELSE (NTC scenario=1, NTC CH to DE AT(Year)*NTC CH to DE AT profile,NTC CH to DE AT(2015)*NTC CH to DE AT profile)
        ~       MW
        ~       Hourly NTC values for DE and AT are added, because their spot markets are coupled as well.
        |

DE AT hourly import NTC=
        IF THEN ELSE(NTC scenario=1, NTC DE AT to CH profile * NTC DE AT to CH(Year), NTC DE AT to CH(2015)*NTC DE AT to CH profile)
        ~       MW
        ~       Hourly NTC values for DE and AT are added, because their spot markets are coupled as well.
        |

NTC CH to IT 2014(
        GET XLS LOOKUPS( 'Data.xlsx'  , '2014' , 'A' , 'H4' ))
        ~       1
        ~                       |

NTC CH to IT profile=
        IF THEN ELSE(NTC year=2013, NTC CH to IT 2013(Lookup Time),
        IF THEN ELSE(NTC year=2014, NTC CH to IT 2014(Lookup Time),0))
        ~       Dmnl
        ~                       |

NTC CH to DE AT 2014(
        GET XLS LOOKUPS( 'Data.xlsx'  , '2014' , 'A' , 'F4' ))
        ~       1
        ~                       |

NTC CH to DE AT profile=
        IF THEN ELSE(NTC year=2013, NTC CH to DE AT 2013(Lookup Time),
        IF THEN ELSE(NTC year=2014, NTC CH to DE AT 2014(Lookup Time),0))
        ~       Dmnl
        ~                       |

IT hourly export NTC=
        IF THEN ELSE(NTC scenario=1,NTC CH to IT(Year)*NTC CH to IT profile,NTC CH to IT(2015)*NTC CH to IT profile)
        ~       MW
        ~       Hourly NTC values for DE and AT are added, because their spot markets are coupled as well.
        |
```

```
IT hourly import NTC=
            IF THEN ELSE (NTC scenario=1,NTC IT to CH profile * NTC IT to CH(Year),NTC IT to CH(\
                        2015)*NTC IT to CH profile)
            ~           MW
            ~           Hourly NTC values for DE and AT are added, because their spot markets are coupled as well.
            |

NTC CH to FR 2014(
            GET XLS LOOKUPS( 'Data.xlsx'  , '2014' , 'A' , 'G4' ))
            ~           1
            ~                       |

NTC CH to FR profile=
            IF THEN ELSE(NTC year=2013, NTC CH to FR 2013(Lookup Time),
            IF THEN ELSE(NTC year=2014, NTC CH to FR 2014(Lookup Time),0))
            ~           Dmnl
            ~                       |

TOTAL EXPORT= INTEG (
            IF THEN ELSE(Year end=1, -TOTAL EXPORT,IF THEN ELSE( "Net import/export balance" < 0\
                         , "Net import/export balance" , 0 )/1000/1000),
                        0)
            ~
            ~                       |

TOTAL IMPORT= INTEG (
            IF THEN ELSE( Year end=1, -TOTAL IMPORT, IF THEN ELSE( "Net import/export balance" >\
                         0 , "Net import/export balance" + FR import contracts amount, 0 + FR import contracts amount
             )/1000/1000),
                        0)
            ~
            ~                       |

NTC CH to DE AT 2013(
            GET XLS LOOKUPS( 'Data.xlsx'  , '2013' , 'A' , 'F4' ))
            ~           1
            ~                       |

FR hourly export NTC=
            IF THEN ELSE(NTC scenario=1,NTC CH to FR(Year)*NTC CH to FR profile,NTC CH to FR(2015\
                        )*NTC CH to FR profile)
            ~           MW
            ~           Hourly NTC values for DE and AT are added, because their spot markets are \
                        coupled as well.
            |

FR hourly import NTC=
            IF THEN ELSE(NTC scenario = 1,NTC FR to CH profile * NTC FR to CH(Year),NTC FR to CH\
                        (2015)*NTC FR to CH profile)
            ~           MW
            ~           Hourly NTC values for DE and AT are added, because their spot markets are \
                        coupled as well.
            |

NTC CH to FR 2013(
            GET XLS LOOKUPS( 'Data.xlsx'  , '2013' , 'A' , 'G4' ))
            ~           1
            ~                       |

NTC scenario=
            1
            ~
            ~           1 = TYNDP ENTSO-E, 2 =  7500 MW (OSORIO & VAN ACKERE, 2016)
            |

NTC CH to IT 2013(
            GET XLS LOOKUPS( 'Data.xlsx'  , '2013' , 'A' , 'H4' ))
            ~           1
            ~                       |

Spot price reference=
            20
            ~
            ~                       |

FR import contracts amount=
            IF THEN ELSE(Spot price>FR import contract price,MIN(0.25*FR import contract+(Spot price\
                        -FR import contract price)/Spot price reference*FR import contract
            ,FR import contract),
            IF THEN ELSE(Spot price=FR import contract price,
            MAX(0,Residual demand-Nuclear available capacity-Waste burning installed capacity-Geothermal installed capacity\
                        -IF THEN ELSE
            (Hydro reservoir opportunity cost<FR import contract price,Hydro reservoir available capacity\
                        ,0)-IF THEN ELSE(Hydro pumped opportunity cost
            <FR import contract price,Hydro pumped available capacity,0)),0))
            ~           MW
            ~                       |

DE AT balance=
```

```
        MAX(MIN(
        IF THEN ELSE(Spot price>DE AT hourly spot,NTC usage*DE AT hourly import NTC+(Spot price\
                -DE AT hourly spot)/Spot price reference
        *DE AT hourly import NTC*NTC usage,NTC export usage*DE AT hourly export NTC
        +(DE AT hourly spot-Spot price)/Spot price reference*DE AT hourly export NTC*NTC usage\
                )
        ,DE AT hourly import NTC),-DE AT hourly export NTC)
        ~       MW
        ~               |

IT balance=
        MAX(MIN(
        IF THEN ELSE(Spot price>IT hourly spot,IT hourly import NTC*NTC usage+(Spot price-IT hourly spot\
                )/Spot price reference
        *IT hourly import NTC*NTC usage,NTC export usage*IT hourly export NTC
        +(IT hourly spot-Spot price)/Spot price reference*IT hourly export NTC*NTC export usage\
                )
        ,IT hourly import NTC),-IT hourly export NTC)
        ~       MW
        ~               |

NTC export usage=
        -0.25
        ~
        ~               |

FR balance=
        MAX(MIN(
        IF THEN ELSE(Spot price>FR hourly spot,NTC usage*FR available import NTC+(Spot price\
                -FR hourly spot)/Spot price reference
        *FR available import NTC*NTC usage,NTC export usage*FR hourly export NTC
        +(FR hourly spot-Spot price)/Spot price reference*FR hourly export NTC*NTC export usage\
                )
        ,FR available import NTC),-FR hourly export NTC)
        ~       MW
        ~               |

Monthly exports= INTEG (
        IF THEN ELSE("Net import/export balance"<0,"Net import/export balance",0)-IF THEN ELSE\
                (Month end=1,Monthly exports*C,0),
                0)
        ~
        ~               |

Import reliance for peak=
        IF THEN ELSE(Peak demand > 0, Peak import/Peak demand , 0 )
        ~
        ~               |

Total import NTC=
        DE AT hourly import NTC+FR hourly import NTC+IT hourly import NTC
        ~
        ~               |

Peak import= INTEG (
        IF THEN ELSE("Net import/export balance">Peak import,"Net import/export balance"*C-Peak import\
                *C,0)-IF THEN ELSE
        (Month end=1,Peak import*C,0),
                0)
        ~
        ~               |

Monthtly imports= INTEG (
        FR import contracts amount+IF THEN ELSE("Net import/export balance">0,"Net import/export balance"\
                ,0)-IF THEN ELSE(Month end=1,Monthtly imports*C,0),
                0)
        ~
        ~               |

Monthly imports net=
        SAMPLE IF TRUE(Month end=1,Monthtly imports+Monthly exports, Monthtly imports+Monthly exports\
                )
        ~
        ~               |

Hydro pumped production amount=
        MIN(MIN(

        MAX(0,Residual demand-Nuclear available capacity-Waste burning installed capacity-IF THEN ELSE\
                (Geothermal price<Hydro pumped opportunity cost
        ,Geothermal installed capacity,0)-IF THEN ELSE(FR import contract price<Hydro pumped opportunity cost\
                ,FR import contract
        ,0)-IF THEN ELSE(Other thermal price<Hydro pumped opportunity cost,Other thermal installed capacity\
                ,0)-IF THEN ELSE(RES CHP price
        <Hydro pumped opportunity cost,RES CHP installed capacity,0)-IF THEN ELSE(CCGT price\
                <Hydro pumped opportunity cost,CCGT installed capacity
        ,0)-IF THEN ELSE(Hydro reservoir opportunity cost<Hydro pumped opportunity cost,Hydro reservoir available capacity\
                ,0))

        ,
```

```
	Pumping installed capacity),

	Hydro pumped available capacity)
	~	MW
	~		|

Hydropower reservoir production=
	Hydro reservoir production amount
	~	MW
	~		|

Hydro reservoir production amount=
	MIN(MIN(

	MAX(0,Residual demand-Nuclear available capacity-Waste burning installed capacity-IF THEN ELSE\
		(Geothermal price<Hydro reservoir opportunity cost
	,Geothermal installed capacity,0)-IF THEN ELSE(FR import contract price<Hydro reservoir opportunity cost\
		,FR import contract
	,0)-IF THEN ELSE(Other thermal price<Hydro reservoir opportunity cost,Other thermal installed capacity\
		,0)-IF THEN ELSE(RES CHP price
	<Hydro reservoir opportunity cost,RES CHP installed capacity,0)-IF THEN ELSE(CCGT price\
		<Hydro reservoir opportunity cost
	,CCGT installed capacity,0)-IF THEN ELSE(Hydro pumped opportunity cost<Hydro reservoir opportunity cost\
		,Hydro pumped available capacity
	,0))

	,Hydropower maximum capacity-Pumping installed capacity),

	Hydro reservoir available capacity)
	~	MW
	~		|

Hydropower pumped production=
	Hydro pumped production amount
	~	MW
	~		|

Hydro reservoir opportunity cost=
	MIN(MAX(

	((1-Relative reservoir capacity)*(3*Spot price yearly average-Foreign price comparison factor\
		*Lowest foreign average price
	))+Foreign price comparison factor*Lowest foreign average price

	+ Hydro adjustment amount * (0.2*((Hydro reference level - Relative reservoir capacity\
		)/Hydro reference level)+0.8*((Hydro reference level lookup
	(Day) - Relative reservoir capacity)/Hydro reference level lookup(Day)))

	,0),150)
	~	CHF/(MW*Hour) [11,200]
	~	Osorio 2016 makes a curvature based on the values of the highest and lowest \
		alternative prices, scarcity price and marginal production cost.

		The added amount means that if the level is 10% too high, it will remove 5 \
		from the price and vice versa. Both the factor and the amount adjust this \
		speed.
	|

Hydro reference 3= INTEG (
	IF THEN ELSE(Month end=1:AND:Month=3,C*Hydro discount factor*Reference level monthly average\
		-C*Hydro discount factor*Hydro reference 3,0),
		0.199)
	~	1
	~		|

Hydro reference 4= INTEG (
	IF THEN ELSE(Month end=1:AND:Month=4,C*Hydro discount factor*Reference level monthly average\
		-C*Hydro discount factor*Hydro reference 4,0),
		0.135)
	~	1
	~		|

Hydro reference 5= INTEG (
	IF THEN ELSE(Month end=1:AND:Month=5,C*Hydro discount factor*Reference level monthly average\
		-C*Hydro discount factor*Hydro reference 5,0),
		0.168)
	~	1
	~		|

Hydro reference 6= INTEG (
	IF THEN ELSE(Month end=1:AND:Month=6,C*Hydro discount factor*Reference level monthly average\
		-C*Hydro discount factor*Hydro reference 6,0),
		0.265)
	~	1
	~		|

Hydro reference 7= INTEG (
	IF THEN ELSE(Month end=1:AND:Month=7,C*Hydro discount factor*Reference level monthly average\
		-C*Hydro discount factor*Hydro reference 7,0),
```

```
                        0.588)
            ~           1
            ~                       |

Hydro reference 8= INTEG (
            IF THEN ELSE(Month end=1:AND:Month=8,C*Hydro discount factor*Reference level monthly average\
                        -C*Hydro discount factor*Hydro reference 8,0),
                        0.772)
            ~           1
            ~                       |

Hydro reference 9= INTEG (
            IF THEN ELSE(Month end=1:AND:Month=9,C*Hydro discount factor*Reference level monthly average\
                        -C*Hydro discount factor*Hydro reference 9,0),
                        0.839)
            ~           1
            ~                       |

Hydro reference 11= INTEG (
            IF THEN ELSE(Month end=1:AND:Month=11,C*Hydro discount factor*Reference level monthly average\
                        -C*Hydro discount factor*Hydro reference 11,0),
                        0.78)
            ~           1
            ~                       |

Hydro reference 12= INTEG (
            IF THEN ELSE(Month end=1:AND:Month=12,C*Hydro discount factor*Reference level monthly average\
                        -C*Hydro discount factor*Hydro reference 12,0),
                        0.637)
            ~           1
            ~                       |

Hydro discount factor=
            0.2
            ~           1
            ~           Vary between 0 and 1. 1 means only very high discounting; only look at \
                        last year. 0 means no discounting, no updating of historic values \
                        2010-2014.
            |

Hydro reference 1= INTEG (
            IF THEN ELSE(Month end=1:AND:Month=1,C*Hydro discount factor*Reference level monthly average\
                        -C*Hydro discount factor*Hydro reference 1,0),
                        0.52)
            ~           1
            ~                       |

Hydro reference 10= INTEG (
            IF THEN ELSE(Month end=1:AND:Month=10,C*Hydro discount factor*Reference level monthly average\
                        -C*Hydro discount factor*Hydro reference 10,0),
                        0.828)
            ~           1
            ~                       |

Hydro reference 2= INTEG (
            IF THEN ELSE(Month end=1:AND:Month=2,C*Hydro discount factor*Reference level monthly average\
                        -C*Hydro discount factor*Hydro reference 2,0),
                        0.342)
            ~           1
            ~                       |

Hydro reference level=
            IF THEN ELSE(Month=1, Hydro reference 1,
            IF THEN ELSE(Month=2, Hydro reference 2,
            IF THEN ELSE(Month=3, Hydro reference 3,
            IF THEN ELSE(Month=4, Hydro reference 4,
            IF THEN ELSE(Month=5, Hydro reference 5,
            IF THEN ELSE(Month=6, Hydro reference 6,
            IF THEN ELSE(Month=7, Hydro reference 7,
            IF THEN ELSE(Month=8, Hydro reference 8,
            IF THEN ELSE(Month=9, Hydro reference 9,
            IF THEN ELSE(Month=10, Hydro reference 10,
            IF THEN ELSE(Month=11, Hydro reference 11, Hydro reference 12)))))))))))

            + (MODULO(Time,730) / 730) * C *

            IF THEN ELSE(Month=1, Hydro reference 2-Hydro reference 1,
            IF THEN ELSE(Month=2, Hydro reference 3-Hydro reference 2,
            IF THEN ELSE(Month=3, Hydro reference 4-Hydro reference 3,
            IF THEN ELSE(Month=4, Hydro reference 5-Hydro reference 4,
            IF THEN ELSE(Month=5, Hydro reference 6-Hydro reference 5,
            IF THEN ELSE(Month=6, Hydro reference 7-Hydro reference 6,
            IF THEN ELSE(Month=7, Hydro reference 8-Hydro reference 7,
            IF THEN ELSE(Month=8, Hydro reference 9-Hydro reference 8,
            IF THEN ELSE(Month=9, Hydro reference 10-Hydro reference 9,
            IF THEN ELSE(Month=10, Hydro reference 11-Hydro reference 10,
            IF THEN ELSE(Month=11, Hydro reference 12-Hydro reference 11, Hydro reference 1-Hydro reference 12\
                        )))))))))))
            ~           1
            ~                       |
```

```
Lookup Time=
        0+MODULO(Time, 8760)*C
        ~       1
        ~       To limit file sizes and the model's startup time only 8760 values per \
                variable are imported. Using 'Time' returns an 'out of bounds' error since \
                we would need 8760*35 values. Taking the remainder of 8760 effectively \
                'resets' the lookup call every year, which is exactly the behavior we want.
        |

Month= INTEG (
        +Month end-12*Year end,
                1)
        ~       Hour
        ~       Runs 1 to 12 and resets
        |

Reference level counter= INTEG (
        Relative reservoir capacity-IF THEN ELSE(Month end=1,Reference level counter*C,0),
                0)
        ~       Hour
        ~               |

Reference level monthly average=
        SAMPLE IF TRUE(Month end=1, Reference level counter / Hours per month, 1)
        ~       1
        ~               |

Foreign price comparison factor=
        0.95
        ~       Dmnl
        ~               |

Fossil existing production=
        IF THEN ELSE(Spot price>Other thermal price,Other thermal installed capacity,
        IF THEN ELSE(Spot price=Other thermal price,
        MAX(0,Residual demand-Nuclear available capacity-Waste burning installed capacity-Geothermal installed capacity\
                -FR import contract-IF THEN ELSE(CCGT price<Other thermal price,CCGT installed capacity\
                ,0)-IF THEN ELSE(Hydro reservoir opportunity cost<Other thermal price,Hydro reservoir available capacity\
                ,0)-IF THEN ELSE(Hydro pumped opportunity cost<Other thermal price,Hydro pumped available capacity\
                ,0)),0))
        ~       MW
        ~               |

Hydro reservoir available capacity=
        MIN(Max regular reservoir capacity*9920/8800*C,Hydropower reservoir*C)
        ~       MW
        ~       9920/8820 to convert between dam capacity and production capacity (see \
                Maximum Hydropower Capacity)
        |

Max reservoir capacity=
        8800/9920*1000*Hydropower maximum capacity/C
        ~       MW*Hour
        ~       Max reservoir capacity = 8800 GWh in 2014 (Reinier) and capacity was 9920 \
                MW (Osorio), so the reservoir capacity grows according to hydro installed \
                capacity. Added a unit factor to displace the time unit in the correlation \
                and avoid a new variables for max capacity GWh, GWh to MWh, MWh reservoir \
                per MW capacity.
        |

Interruptible contracts utilization=
        IF THEN ELSE(Spot price>Interruptible contracts price,Interruptible contracts,
        IF THEN ELSE(Spot price=Interruptible contracts price,MAX(0,Residual demand-Hydro reservoir available capacity\
                -Hydro pumped available capacity-Nuclear available capacity-Waste burning installed capacity\
                -Other thermal installed capacity-CCGT installed capacity-Geothermal installed capacity\
                -FR import contract-RES CHP installed capacity),0))
        ~       MW
        ~               |

Hydropower capacity ratio pumping=
        Pumping installed capacity/Hydropower maximum capacity
        ~       Dmnl
        ~       % of the total installed turbine capacity that doubles as pump-turbine
        |

CCGT production=
        IF THEN ELSE(Spot price>CCGT price,CCGT installed capacity,
        IF THEN ELSE(Spot price=CCGT price,
        MAX(0,Residual demand-Nuclear available capacity-Waste burning installed capacity-Geothermal installed capacity\
                -FR import contract-IF THEN ELSE(Other thermal price<CCGT price,Other thermal installed capacity\
                ,0)-IF THEN ELSE(RES CHP price<CCGT price,RES CHP installed capacity,0)-IF THEN ELSE\
                (Hydro reservoir opportunity cost<CCGT price,Hydro reservoir available capacity,0)-\
                IF THEN ELSE
        (Hydro pumped opportunity cost<CCGT price,Hydro pumped available capacity,0)),0))
        ~       MW
        ~               |

Spot price=
        SIMULTANEOUS(
```

```
MAX(Price floor,
IF THEN ELSE(Residual demand <= 0, 0,

MIN(IF THEN ELSE(MIN(Nuclear available capacity+Waste burning installed capacity+Geothermal installed capacity\
        +FR import contract+Other thermal installed capacity+RES CHP installed capacity+Hydro reservoir available capacity\
        +Hydro pumped available capacity+CCGT installed capacity+Interruptible contracts,Residual demand\
        )=Residual demand,
MAX(Nuclear price,MAX(Waste burning price,MAX(Geothermal price,MAX(FR import contract price\
        ,MAX(Other thermal price,MAX(RES CHP price,MAX(Hydro reservoir opportunity cost,MAX\
        (CCGT price,MAX(Hydro pumped opportunity cost,Interruptible contracts price))))))))\
        ),VOLL),

MIN(IF THEN ELSE(MIN(Nuclear available capacity+Waste burning installed capacity+Geothermal installed capacity\
        +FR import contract+Other thermal installed capacity+RES CHP installed capacity+Hydro reservoir available capacity\
        +Hydro pumped available capacity+CCGT installed capacity,Residual demand)=Residual demand\
        ,
MAX(Nuclear price,MAX(Waste burning price,MAX(Geothermal price,MAX(FR import contract price\
        ,MAX(Other thermal price,MAX(RES CHP price,MAX(Hydro reservoir opportunity cost,MAX\
        (CCGT price,Hydro pumped opportunity cost)))))))),VOLL),

MIN(IF THEN ELSE(MIN(Nuclear available capacity+Waste burning installed capacity+Geothermal installed capacity\
        +FR import contract+Other thermal installed capacity+RES CHP installed capacity+Hydro reservoir available capacity\
        +Hydro pumped available capacity,Residual demand)=Residual demand,
MAX(Nuclear price,MAX(Waste burning price,MAX(Geothermal price,MAX(FR import contract price\
        ,MAX(Other thermal price,MAX(RES CHP price,MAX(Hydro reservoir opportunity cost,Hydro pumped opportunity cost\
        ))))))),VOLL),

MIN(IF THEN ELSE(MIN(Nuclear available capacity+Waste burning installed capacity+Geothermal installed capacity\
        +FR import contract+Other thermal installed capacity+RES CHP installed capacity+Hydro reservoir available capacity\
        +CCGT installed capacity,Residual demand)=Residual demand,
MAX(Nuclear price,MAX(Waste burning price,MAX(Geothermal price,MAX(FR import contract price\
        ,MAX(Other thermal price,MAX(RES CHP price,MAX(Hydro reservoir opportunity cost,CCGT price\
        ))))))),VOLL),

MIN(IF THEN ELSE(MIN(Nuclear available capacity+Waste burning installed capacity+Geothermal installed capacity\
        +FR import contract+Other thermal installed capacity+RES CHP installed capacity+Hydro pumped available capacity\
        +CCGT installed capacity,Residual demand)=Residual demand,
MAX(Nuclear price,MAX(Waste burning price,MAX(Geothermal price,MAX(FR import contract price\
        ,MAX(Other thermal price,MAX(RES CHP price,MAX(Hydro pumped opportunity cost,CCGT price\
        ))))))),VOLL),

MIN(IF THEN ELSE(MIN(Nuclear available capacity+Waste burning installed capacity+Geothermal installed capacity\
        +FR import contract+Other thermal installed capacity+Hydro reservoir available capacity\
        +Hydro pumped available capacity+CCGT installed capacity,Residual demand)=Residual demand\
        ,
MAX(Nuclear price,MAX(Waste burning price,MAX(Geothermal price,MAX(FR import contract price\
        ,MAX(Other thermal price,MAX(Hydro reservoir opportunity cost,MAX(Hydro pumped opportunity cost\
        ,CCGT price))))))),VOLL),

MIN(IF THEN ELSE(MIN(Nuclear available capacity+Waste burning installed capacity+Geothermal installed capacity\
        +FR import contract+Other thermal installed capacity+Hydro reservoir available capacity\
        +Hydro pumped available capacity,Residual demand)=Residual demand,
MAX(Nuclear price,MAX(Waste burning price,MAX(Geothermal price,MAX(FR import contract price\
        ,MAX(Other thermal price,MAX(Hydro reservoir opportunity cost,Hydro pumped opportunity cost\
        )))))),VOLL),

MIN(IF THEN ELSE(MIN(Nuclear available capacity+Waste burning installed capacity+Geothermal installed capacity\
        +FR import contract+Other thermal installed capacity+Hydro reservoir available capacity\
        +CCGT installed capacity,Residual demand)=Residual demand,
MAX(Nuclear price,MAX(Waste burning price,MAX(Geothermal price,MAX(FR import contract price\
        ,MAX(Other thermal price,MAX(Hydro reservoir opportunity cost,CCGT price)))))),VOLL\
        ),

MIN(IF THEN ELSE(MIN(Nuclear available capacity+Waste burning installed capacity+Geothermal installed capacity\
        +FR import contract+Other thermal installed capacity+Hydro pumped available capacity\
        +CCGT installed capacity,Residual demand)=Residual demand,
MAX(Nuclear price,MAX(Waste burning price,MAX(Geothermal price,MAX(FR import contract price\
        ,MAX(Other thermal price,MAX(Hydro pumped opportunity cost,CCGT price)))))),VOLL),

MIN(IF THEN ELSE(MIN(Nuclear available capacity+Waste burning installed capacity+Geothermal installed capacity\
        +FR import contract+Hydro reservoir available capacity+Hydro pumped available capacity\
        +CCGT installed capacity,Residual demand)=Residual demand,
MAX(Nuclear price,MAX(Waste burning price,MAX(Geothermal price,MAX(FR import contract price\
        ,MAX(Hydro reservoir opportunity cost,MAX(Hydro pumped opportunity cost,CCGT price)\
        ))))),VOLL),

MIN(IF THEN ELSE(MIN(Nuclear available capacity+Waste burning installed capacity+Geothermal installed capacity\
        +FR import contract+Other thermal installed capacity+CCGT installed capacity,Residual demand\
        )=Residual demand,
MAX(Nuclear price,MAX(Waste burning price,MAX(Geothermal price,MAX(FR import contract price\
        ,MAX(Other thermal price,CCGT price))))),VOLL),

MIN(IF THEN ELSE(MIN(Nuclear available capacity+Waste burning installed capacity+Geothermal installed capacity\
        +FR import contract+Other thermal installed capacity+Hydro reservoir available capacity\
        ,Residual demand)=Residual demand,
MAX(Nuclear price,MAX(Waste burning price,MAX(Geothermal price,MAX(FR import contract price\
        ,MAX(Other thermal price,Hydro reservoir opportunity cost))))),VOLL),

MIN(IF THEN ELSE(MIN(Nuclear available capacity+Waste burning installed capacity+Geothermal installed capacity\
        +FR import contract+Other thermal installed capacity+Hydro pumped available capacity\
```

```
                ,Residual demand)=Residual demand,
        MAX(Nuclear price,MAX(Waste burning price,MAX(Geothermal price,MAX(FR import contract price\
                ,MAX(Other thermal price,Hydro pumped opportunity cost))))),VOLL),

        MIN(IF THEN ELSE(MIN(Nuclear available capacity+Waste burning installed capacity+Geothermal installed capacity\
                +FR import contract+CCGT installed capacity,Residual demand)=Residual demand,
        MAX(Nuclear price,MAX(Waste burning price,MAX(Geothermal price,MAX(FR import contract price\
                ,CCGT price)))),VOLL),

        MIN(IF THEN ELSE(MIN(Nuclear available capacity+Waste burning installed capacity+Geothermal installed capacity\
                +FR import contract+Hydro reservoir available capacity,Residual demand)=Residual demand\
                ,
        MAX(Nuclear price,MAX(Waste burning price,MAX(Geothermal price,MAX(FR import contract price\
                ,Hydro reservoir opportunity cost)))),VOLL),

        MIN(IF THEN ELSE(MIN(Nuclear available capacity+Waste burning installed capacity+Geothermal installed capacity\
                +FR import contract+Hydro pumped available capacity,Residual demand)=Residual demand\
                ,
        MAX(Nuclear price,MAX(Waste burning price,MAX(Geothermal price,MAX(FR import contract price\
                ,Hydro pumped opportunity cost)))),VOLL),

        MIN(IF THEN ELSE(MIN(Nuclear available capacity+Waste burning installed capacity+Geothermal installed capacity\
                +Hydro reservoir available capacity+Hydro pumped available capacity,Residual demand\
                )=Residual demand,
        MAX(Nuclear price,MAX(Waste burning price,MAX(Geothermal price,MAX(Hydro reservoir opportunity cost\
                ,Hydro pumped opportunity cost)))),VOLL),

        MIN(IF THEN ELSE(MIN(Nuclear available capacity+Waste burning installed capacity+Geothermal installed capacity\
                +Hydro reservoir available capacity,Residual demand)=Residual demand,
        MAX(Nuclear price,MAX(Waste burning price,MAX(Geothermal price,Hydro reservoir opportunity cost\
                ))),VOLL),

        MIN(IF THEN ELSE(MIN(Nuclear available capacity+Waste burning installed capacity+Geothermal installed capacity\
                +Hydro pumped available capacity,Residual demand)=Residual demand,
        MAX(Nuclear price,MAX(Waste burning price,MAX(Geothermal price,Hydro pumped opportunity cost\
                ))),VOLL),

        MIN(IF THEN ELSE(MIN(Nuclear available capacity+Waste burning installed capacity+Hydro reservoir available capacity\
                +Hydro pumped available capacity,Residual demand)=Residual demand,
        MAX(Nuclear price,MAX(Waste burning price,MAX(Hydro reservoir opportunity cost,Hydro pumped opportunity cost\
                ))),VOLL),

        MIN(IF THEN ELSE(MIN(Nuclear available capacity+Waste burning installed capacity+Hydro pumped available capacity\
                ,Residual demand)=Residual demand,
        MAX(Nuclear price,MAX(Waste burning price,Hydro pumped opportunity cost)),VOLL),

        MIN(IF THEN ELSE(MIN(Nuclear available capacity+Waste burning installed capacity+Hydro reservoir available capacity\
                ,Residual demand)=Residual demand,
        MAX(Nuclear price,MAX(Waste burning price,Hydro reservoir opportunity cost)),VOLL),

        MIN(IF THEN ELSE(MIN(Nuclear available capacity+Waste burning installed capacity,Residual demand\
                )=Residual demand,
        MAX(Nuclear price,Waste burning price),VOLL),

        MIN(IF THEN ELSE(MIN(Nuclear available capacity,Residual demand)=Residual demand,
        Nuclear price,VOLL),VOLL)))))))))))))))))))))))))),30)
        ~       CHF/(MW*Hour)
        ~               |

Hydropower pumping amount=
        IF THEN ELSE(Hydro pumped production amount=0,
        IF THEN ELSE(Spot price/Pumping efficiency<Hydro pumped opportunity cost,
        MIN(Pumping installed capacity,MAX((Max pumped reservoir capacity-Hydropower pumped reservoir\
                )*C,0)),0),0)
        ~       MW
        ~       If there is no production of hydropower from the pumped reservoirs, and \
                the pumping opportunity cost is high enough compared to the spot price, \
                there will be pumping either the max capacity, or the maximum water (in \
                MWh) that can be added over one hour (MWh/h=MW).
        |

Hydro adjustment amount=
        200
        ~       CHF/(MW*Hour)
        ~               |

Waste burning production=
        IF THEN ELSE(Spot price>Waste burning price,Waste burning installed capacity,
        IF THEN ELSE(Spot price=Waste burning price,MAX(0,Residual demand-Nuclear available capacity\
                ),0))
        ~       MW
        ~               |

Hydro pumped available capacity=
        MIN(Max pumped reservoir capacity*9920/8800*C,Hydropower pumped reservoir*C)
        ~       MW
        ~       9920/8820 to convert between dam capacity and production capacity (see \
                Maximum Hydropower Capacity)
        |
```

```
Demand forecast=
        Demand factor hourly*FORECAST(Demand yearly,3*Hours per year,3*Hours per year)
        ~       MW
        ~               |

Geothermal production=
        IF THEN ELSE(Spot price>Geothermal price,Geothermal installed capacity,
        IF THEN ELSE(Spot price=Geothermal price,MAX(0,Residual demand-Nuclear available capacity\
                -Waste burning installed capacity-IF THEN ELSE(Hydro pumped opportunity cost<Geothermal price\
                ,Hydro pumped available capacity,0)-IF THEN ELSE(Hydro reservoir opportunity cost<Geothermal price\
                ,Hydro reservoir available capacity,0)),0))
        ~       MW
        ~               |

RES CHP production=
        IF THEN ELSE(Spot price>RES CHP price,RES CHP installed capacity,
        IF THEN ELSE(Spot price=RES CHP price,
        MAX(0,Residual demand-Nuclear available capacity-Waste burning installed capacity-Geothermal installed capacity\
                -FR import contract-Other thermal installed capacity-IF THEN ELSE(CCGT price<RES CHP price\
                ,CCGT installed capacity,0)-IF THEN ELSE(Hydro reservoir opportunity cost<RES CHP price\
                ,Hydro reservoir available capacity,0)-IF THEN ELSE(Hydro pumped opportunity cost<RES CHP price\
                ,Hydro pumped available capacity,0)),0))
        ~       MW
        ~               |

Spot price forecast=
        SIMULTANEOUS(
        MAX(Price floor,
        IF THEN ELSE(Residual demand forecast <= 0, 0,

        MIN(IF THEN ELSE(MIN(Nuclear installed capacity forecast+Waste burning installed capacity\
                +Geothermal installed capacity+FR import contracts maximum forecast+Other thermal installed capacity\
                +RES CHP installed capacity+Hydro reservoir available capacity+Hydro pumped available capacity\
                +CCGT installed capacity forecast+Interruptible contracts,Residual demand forecast)\
                =Residual demand forecast,
        MAX(Nuclear price,MAX(Waste burning price,MAX(Geothermal price,MAX(FR import contract price\
                ,MAX(Other thermal price,MAX(RES CHP price,MAX(Hydro reservoir opportunity cost,MAX\
                (CCGT price,MAX(Hydro pumped opportunity cost,Interruptible contracts price))))))))\
                ),VOLL),

        MIN(IF THEN ELSE(MIN(Nuclear installed capacity forecast+Waste burning installed capacity\
                +Geothermal installed capacity+FR import contracts maximum forecast+Other thermal installed capacity\
                +RES CHP installed capacity+Hydro reservoir available capacity+Hydro pumped available capacity\
                +CCGT installed capacity forecast,Residual demand forecast)=Residual demand forecast\
                ,
        MAX(Nuclear price,MAX(Waste burning price,MAX(Geothermal price,MAX(FR import contract price\
                ,MAX(Other thermal price,MAX(RES CHP price,MAX(Hydro reservoir opportunity cost,MAX\
                (CCGT price,Hydro pumped opportunity cost)))))))),VOLL),

        MIN(IF THEN ELSE(MIN(Nuclear installed capacity forecast+Waste burning installed capacity\
                +Geothermal installed capacity+FR import contracts maximum forecast+Other thermal installed capacity\
                +RES CHP installed capacity+Hydro reservoir available capacity+Hydro pumped available capacity\
                ,Residual demand forecast)=Residual demand forecast,
        MAX(Nuclear price,MAX(Waste burning price,MAX(Geothermal price,MAX(FR import contract price\
                ,MAX(Other thermal price,MAX(RES CHP price,MAX(Hydro reservoir opportunity cost,Hydro pumped opportunity cost\
                ))))))),VOLL),

        MIN(IF THEN ELSE(MIN(Nuclear installed capacity forecast+Waste burning installed capacity\
                +Geothermal installed capacity+FR import contracts maximum forecast+Other thermal installed capacity\
                +RES CHP installed capacity+Hydro reservoir available capacity+CCGT installed capacity forecast\
                ,Residual demand forecast)=Residual demand forecast,
        MAX(Nuclear price,MAX(Waste burning price,MAX(Geothermal price,MAX(FR import contract price\
                ,MAX(Other thermal price,MAX(RES CHP price,MAX(Hydro reservoir opportunity cost,CCGT price\
                ))))))),VOLL),

        MIN(IF THEN ELSE(MIN(Nuclear installed capacity forecast+Waste burning installed capacity\
                +Geothermal installed capacity+FR import contracts maximum forecast+Other thermal installed capacity\
                +RES CHP installed capacity+Hydro pumped available capacity+CCGT installed capacity forecast\
                ,Residual demand forecast)=Residual demand forecast,
        MAX(Nuclear price,MAX(Waste burning price,MAX(Geothermal price,MAX(FR import contract price\
                ,MAX(Other thermal price,MAX(RES CHP price,MAX(Hydro pumped opportunity cost,CCGT price\
                ))))))),VOLL),

        MIN(IF THEN ELSE(MIN(Nuclear installed capacity forecast+Waste burning installed capacity\
                +Geothermal installed capacity+FR import contracts maximum forecast+Other thermal installed capacity\
                +Hydro reservoir available capacity+Hydro pumped available capacity+CCGT installed capacity forecast\
                ,Residual demand forecast)=Residual demand forecast,
        MAX(Nuclear price,MAX(Waste burning price,MAX(Geothermal price,MAX(FR import contract price\
                ,MAX(Other thermal price,MAX(Hydro reservoir opportunity cost,MAX(Hydro pumped opportunity cost\
                ,CCGT price))))))),VOLL),

        MIN(IF THEN ELSE(MIN(Nuclear installed capacity forecast+Waste burning installed capacity\
                +Geothermal installed capacity+FR import contracts maximum forecast+Other thermal installed capacity\
                +Hydro reservoir available capacity+Hydro pumped available capacity,Residual demand forecast\
                )=Residual demand forecast,
        MAX(Nuclear price,MAX(Waste burning price,MAX(Geothermal price,MAX(FR import contract price\
                ,MAX(Other thermal price,MAX(Hydro reservoir opportunity cost,Hydro pumped opportunity cost\
                )))))),VOLL),

        MIN(IF THEN ELSE(MIN(Nuclear installed capacity forecast+Waste burning installed capacity\
```

```
        +Geothermal installed capacity+FR import contracts maximum forecast+Other thermal installed capacity\
        +Hydro reservoir available capacity+CCGT installed capacity forecast,Residual demand forecast\
        )=Residual demand forecast,
MAX(Nuclear price,MAX(Waste burning price,MAX(Geothermal price,MAX(FR import contract price\
        ,MAX(Other thermal price,MAX(Hydro reservoir opportunity cost,CCGT price)))))),VOLL\
        ),

MIN(IF THEN ELSE(MIN(Nuclear installed capacity forecast+Waste burning installed capacity\
        +Geothermal installed capacity+FR import contracts maximum forecast+Other thermal installed capacity\
        +Hydro pumped available capacity+CCGT installed capacity forecast,Residual demand forecast\
        )=Residual demand forecast,
MAX(Nuclear price,MAX(Waste burning price,MAX(Geothermal price,MAX(FR import contract price\
        ,MAX(Other thermal price,MAX(Hydro pumped opportunity cost,CCGT price)))))),VOLL),

MIN(IF THEN ELSE(MIN(Nuclear installed capacity forecast+Waste burning installed capacity\
        +Geothermal installed capacity+FR import contracts maximum forecast+Hydro reservoir available capacity\
        +Hydro pumped available capacity+CCGT installed capacity forecast,Residual demand forecast\
        )=Residual demand forecast,
MAX(Nuclear price,MAX(Waste burning price,MAX(Geothermal price,MAX(FR import contract price\
        ,MAX(Hydro reservoir opportunity cost,MAX(Hydro pumped opportunity cost,CCGT price)\
        ))))),VOLL),

MIN(IF THEN ELSE(MIN(Nuclear installed capacity forecast+Waste burning installed capacity\
        +Geothermal installed capacity+FR import contracts maximum forecast+Other thermal installed capacity\
        +CCGT installed capacity forecast,Residual demand forecast)=Residual demand forecast\
        ,
MAX(Nuclear price,MAX(Waste burning price,MAX(Geothermal price,MAX(FR import contract price\
        ,MAX(Other thermal price,CCGT price))))),VOLL),

MIN(IF THEN ELSE(MIN(Nuclear installed capacity forecast+Waste burning installed capacity\
        +Geothermal installed capacity+FR import contracts maximum forecast+Other thermal installed capacity\
        +Hydro reservoir available capacity,Residual demand forecast)=Residual demand forecast\
        ,
MAX(Nuclear price,MAX(Waste burning price,MAX(Geothermal price,MAX(FR import contract price\
        ,MAX(Other thermal price,Hydro reservoir opportunity cost))))),VOLL),

MIN(IF THEN ELSE(MIN(Nuclear installed capacity forecast+Waste burning installed capacity\
        +Geothermal installed capacity+FR import contracts maximum forecast+Other thermal installed capacity\
        +Hydro pumped available capacity,Residual demand forecast)=Residual demand forecast\
        ,
MAX(Nuclear price,MAX(Waste burning price,MAX(Geothermal price,MAX(FR import contract price\
        ,MAX(Other thermal price,Hydro pumped opportunity cost))))),VOLL),

MIN(IF THEN ELSE(MIN(Nuclear installed capacity forecast+Waste burning installed capacity\
        +Geothermal installed capacity+FR import contracts maximum forecast+CCGT installed capacity forecast\
        ,Residual demand forecast)=Residual demand forecast,
MAX(Nuclear price,MAX(Waste burning price,MAX(Geothermal price,MAX(FR import contract price\
        ,CCGT price)))),VOLL),

MIN(IF THEN ELSE(MIN(Nuclear installed capacity forecast+Waste burning installed capacity\
        +Geothermal installed capacity+FR import contracts maximum forecast+Hydro reservoir available capacity\
        ,Residual demand forecast)=Residual demand forecast,
MAX(Nuclear price,MAX(Waste burning price,MAX(Geothermal price,MAX(FR import contract price\
        ,Hydro reservoir opportunity cost)))),VOLL),

MIN(IF THEN ELSE(MIN(Nuclear installed capacity forecast+Waste burning installed capacity\
        +Geothermal installed capacity+FR import contracts maximum forecast+Hydro pumped available capacity\
        ,Residual demand forecast)=Residual demand forecast,
MAX(Nuclear price,MAX(Waste burning price,MAX(Geothermal price,MAX(FR import contract price\
        ,Hydro pumped opportunity cost)))),VOLL),

MIN(IF THEN ELSE(MIN(Nuclear installed capacity forecast+Waste burning installed capacity\
        +Geothermal installed capacity+Hydro reservoir available capacity+Hydro pumped available capacity\
        ,Residual demand forecast)=Residual demand forecast,
MAX(Nuclear price,MAX(Waste burning price,MAX(Geothermal price,MAX(Hydro reservoir opportunity cost\
        ,Hydro pumped opportunity cost)))),VOLL),

MIN(IF THEN ELSE(MIN(Nuclear installed capacity forecast+Waste burning installed capacity\
        +Geothermal installed capacity+Hydro reservoir available capacity,Residual demand forecast\
        )=Residual demand forecast,
MAX(Nuclear price,MAX(Waste burning price,MAX(Geothermal price,Hydro reservoir opportunity cost\
        ))),VOLL),

MIN(IF THEN ELSE(MIN(Nuclear installed capacity forecast+Waste burning installed capacity\
        +Geothermal installed capacity+Hydro pumped available capacity,Residual demand forecast\
        )=Residual demand forecast,
MAX(Nuclear price,MAX(Waste burning price,MAX(Geothermal price,Hydro pumped opportunity cost\
        ))),VOLL),

MIN(IF THEN ELSE(MIN(Nuclear installed capacity forecast+Waste burning installed capacity\
        +Hydro reservoir available capacity+Hydro pumped available capacity,Residual demand forecast\
        )=Residual demand forecast,
MAX(Nuclear price,MAX(Waste burning price,MAX(Hydro reservoir opportunity cost,Hydro pumped opportunity cost\
        ))),VOLL),

MIN(IF THEN ELSE(MIN(Nuclear installed capacity forecast+Waste burning installed capacity\
        +Hydro pumped available capacity,Residual demand forecast)=Residual demand forecast\
        ,
MAX(Nuclear price,MAX(Waste burning price,Hydro pumped opportunity cost)),VOLL),
```

```
        MIN(IF THEN ELSE(MIN(Nuclear installed capacity forecast+Waste burning installed capacity\
                +Hydro reservoir available capacity,Residual demand forecast)=Residual demand forecast\
                ,
        MAX(Nuclear price,MAX(Waste burning price,Hydro reservoir opportunity cost)),VOLL),

        MIN(IF THEN ELSE(MIN(Nuclear installed capacity forecast+Waste burning installed capacity\
                ,Residual demand forecast)=Residual demand forecast,
        MAX(Nuclear price,Waste burning price),VOLL),

        MIN(IF THEN ELSE(MIN(Nuclear installed capacity forecast,Residual demand forecast)=Residual demand forecast\
                ,
        Nuclear price,VOLL),VOLL)))))))))))))))))))))))))),30)
        ~       CHF/(MW*Hour)
        ~               |

Nuclear production=
        IF THEN ELSE(Spot price>Nuclear price,Nuclear available capacity,
        IF THEN ELSE(Spot price=Nuclear price,MAX(0,Residual demand),0))
        ~       MW
        ~               |

Hydro reference level lookup=
        GET XLS LOOKUPS( 'Data.xlsx'  , 'Hydro' , 'A' , 'B4' )
        ~       1
        ~       Unused now. Historical hydro profile, takes as input <Day>, outputs value \
                between 0 and 1.
        |

Day=
        1+INTEGER((MODULO(Time,8760))/24)
        ~       Hour
        ~       Values 1-365
        |

NTC FR 2014(
        GET XLS LOOKUPS( 'Data.xlsx'  , '2014' , 'A' , 'J4' ))
        ~       1
        ~               |

Solar installed capacity= INTEG (
        Solar completion rate-Solar decomissioning rate,
                200)
        ~       MW
        ~               |

Maximal theoretical solar capacity=
        19702
        ~       MW
        ~       Osorio (2016)
        |

NTC IT 2013(
        GET XLS LOOKUPS( 'Data.xlsx'  , '2013' , 'A' , 'K4' ))
        ~       1
        ~               |

NTC IT 2014(
        GET XLS LOOKUPS( 'Data.xlsx'  , '2014' , 'A' , 'K4' ))
        ~       1
        ~               |

ROR data 2011(
        GET XLS LOOKUPS( 'Data.xlsx' , '2011' , 'A' , 'N4' ))
        ~       MW/((MW*Hour)/year)
        ~               |

FR hourly spot=
        FR yearly average
        *
        FR spot profile
        ~       CHF/(MW*Hour)
        ~               |

Swiss hourly electricity demand=
        Demand factor hourly*Demand yearly
        ~       MW
        ~               |

Total VRES production forecast=
        Solar hourly production factor*FORECAST(Solar installed capacity,3*Hours per year,3*\
                Hours per year)+
        Wind hourly production factor*FORECAST(Wind installed capacity,3*Hours per year,3*Hours per year\
                )+
        ROR hourly production factor*FORECAST(ROR yearly production,3*Hours per year,3*Hours per year\
                )
        ~       MW
        ~               |

Solar factor 1996(
        GET XLS LOOKUPS( 'Data.xlsx'  , '1996' , 'A' , 'L4' ))
```

```
            ~           Dmnl
            ~                       |

Solar factor 1997(
            GET XLS LOOKUPS( 'Data.xlsx'  , '1997' , 'A' , 'L4' ))
            ~           Dmnl
            ~                       |

Solar production=
            Solar installed capacity*Solar hourly production factor
            ~           MW
            ~                       |

NTC DE AT 2013(
            GET XLS LOOKUPS( 'Data.xlsx'  , '2013' , 'A' , 'I4' ))
            ~           1
            ~                       |

NTC DE AT 2014(
            GET XLS LOOKUPS( 'Data.xlsx'  , '2014' , 'A' , 'I4' ))
            ~           1
            ~                       |

FR spot 2010(
            GET XLS LOOKUPS( 'Data.xlsx'  , '2010' , 'A' , 'D4' ))
            ~           1
            ~                       |

NTC DE AT to CH profile=
            IF THEN ELSE(NTC year=2013, NTC DE AT 2013(Lookup Time),
            IF THEN ELSE(NTC year=2014, NTC DE AT 2014(Lookup Time),0))
            ~           Dmnl
            ~                       |

NTC FR 2013(
            GET XLS LOOKUPS( 'Data.xlsx'  , '2013' , 'A' , 'J4' ))
            ~           1
            ~                       |

DE AT spot 2010(
            GET XLS LOOKUPS( 'Data.xlsx'  , '2010' , 'A' , 'C4' ))
            ~           1
            ~                       |

FR spot 2014(
            GET XLS LOOKUPS( 'Data.xlsx'  , '2014' , 'A' , 'D4' ))
            ~           1
            ~                       |

NTC FR to CH profile=
            IF THEN ELSE(NTC year=2013, NTC FR 2013(Lookup Time),
            IF THEN ELSE(NTC year=2014, NTC FR 2014(Lookup Time),0))
            ~           Dmnl
            ~                       |

DE AT spot 2013(
            GET XLS LOOKUPS( 'Data.xlsx'  , '2013' , 'A' , 'C4' ))
            ~           1
            ~                       |

DE AT spot 2014(
            GET XLS LOOKUPS( 'Data.xlsx'  , '2014' , 'A' , 'C4' ))
            ~           1
            ~                       |

DE AT spot profile=
            IF THEN ELSE(Profile year = 2010, DE AT spot 2010(Lookup Time),
            IF THEN ELSE(Profile year = 2011, DE AT spot 2011(Lookup Time),
            IF THEN ELSE(Profile year = 2012, DE AT spot 2012(Lookup Time),
            IF THEN ELSE(Profile year = 2013, DE AT spot 2013(Lookup Time),
            IF THEN ELSE(Profile year = 2014, DE AT spot 2014(Lookup Time),0)))))
            ~           Dmnl
            ~                       |

NTC IT to CH profile=
            IF THEN ELSE(NTC year=2013, NTC IT 2013(Lookup Time),
            IF THEN ELSE(NTC year=2014, NTC IT 2014(Lookup Time),0))
            ~           Dmnl
            ~                       |

ROR data 2013(
            GET XLS LOOKUPS( 'Data.xlsx' , '2013' , 'A' , 'N4' ))
            ~           MW/((MW*Hour)/year)
            ~                       |

NTC year=
            2013
            ~           1
            ~           2013 or 2014
            |
```

```
Solar decomissioning rate=
        Solar installed capacity/(Solar lifetime)
        ~       MW/Hour
        ~               |

ROR hourly production factor=
        IF THEN ELSE(Profile year = 2010, ROR data 2010(Lookup Time),
        IF THEN ELSE(Profile year = 2011, ROR data 2011(Lookup Time),
        IF THEN ELSE(Profile year = 2012, ROR data 2012(Lookup Time),
        IF THEN ELSE(Profile year = 2013, ROR data 2013(Lookup Time),
        IF THEN ELSE(Profile year = 2014, ROR data 2014(Lookup Time),0)))))
        ~       MW/((MW*Hour)/year)
        ~       GWh % of GWh per year total production
                OR: MWh (per hour) per MWh per year
        |

IT spot 2011(
        GET XLS LOOKUPS( 'Data.xlsx'  , '2011' , 'A' , 'E4' ))
        ~       1
        ~               |

Solar factor 1998(
        GET XLS LOOKUPS( 'Data.xlsx'  , '1998' , 'A' , 'L4' ))
        ~       Dmnl
        ~               |

Solar factor 1999(
        GET XLS LOOKUPS( 'Data.xlsx'  , '1999' , 'A' , 'L4' ))
        ~       Dmnl
        ~               |

Solar factor 2000(
        GET XLS LOOKUPS( 'Data.xlsx'  , '2000' , 'A' , 'L4' ))
        ~       Dmnl
        ~               |

Solar factor hourly=
        IF THEN ELSE(PV year = 1996, Solar factor 1996(Lookup Time),
        IF THEN ELSE(PV year = 1997, Solar factor 1997(Lookup Time),
        IF THEN ELSE(PV year = 1998, Solar factor 1998(Lookup Time),
        IF THEN ELSE(PV year = 1999, Solar factor 1999(Lookup Time),
        IF THEN ELSE(PV year = 2000, Solar factor 2000(Lookup Time),0)))))
        ~       MW/MW
        ~               |

Solar hourly production factor=
        Solar utilization factor*Solar factor hourly
        ~       MW/MW
        ~       kWh/kWinstalled
                So: MWh per hour per MW installed, or MW/MW / Dmnl
        |

Wind hourly production factor=
        Wind utilization factor*Wind factor hourly
        ~       MW/MW
        ~       kWh/kWinstalled
                So: MWh per hour per MW installed, or MW/MW / Dmnl
        |

ROR data 2014(
        GET XLS LOOKUPS( 'Data.xlsx' , '2014' , 'A' , 'N4' ))
        ~       MW/((MW*Hour)/year)
        ~               |

DE AT spot 2011(
        GET XLS LOOKUPS( 'Data.xlsx'  , '2011' , 'A' , 'C4' ))
        ~       1
        ~               |

DE AT spot 2012(
        GET XLS LOOKUPS( 'Data.xlsx'  , '2012' , 'A' , 'C4' ))
        ~       1
        ~               |

Solar relative installed capacity=
        Solar installed capacity/Maximal theoretical solar capacity
        ~       MW/MW
        ~               |

FR spot profile=
        IF THEN ELSE(Profile year = 2010, FR spot 2010(Lookup Time),
        IF THEN ELSE(Profile year = 2011, FR spot 2011(Lookup Time),
        IF THEN ELSE(Profile year = 2012, FR spot 2012(Lookup Time),
        IF THEN ELSE(Profile year = 2013, FR spot 2013(Lookup Time),
        IF THEN ELSE(Profile year = 2014, FR spot 2014(Lookup Time),0)))))
        ~       Dmnl
        ~               |

ROR data 2012(
```

```
            GET XLS LOOKUPS( 'Data.xlsx' , '2012' , 'A' , 'N4' ))
            ~           MW/((MW*Hour)/year)
            ~                       |

Wind utilization data(
            GET XLS LOOKUPS( 'Data.xlsx' , 'Wind' , 'A' , 'B4' ))
            ~           1
            ~                       |

Inflow data 2011(
            GET XLS LOOKUPS( 'Data.xlsx' , '2011' , 'A' , 'M4' ))
            ~           MW*Hour/Hour/(MW*Hour/year)
            ~                       |

Wind utilization factor=
            Wind utilization data(Wind relative installed capacity)
            ~           1
            ~                       |

IT spot 2010(
            GET XLS LOOKUPS( 'Data.xlsx'  , '2010' , 'A' , 'E4' ))
            ~           1
            ~                       |

IT spot 2012(
            GET XLS LOOKUPS( 'Data.xlsx'  , '2012' , 'A' , 'E4' ))
            ~           1
            ~                       |

FR spot 2011(
            GET XLS LOOKUPS( 'Data.xlsx'  , '2011' , 'A' , 'D4' ))
            ~           1
            ~                       |

IT spot 2014(
            GET XLS LOOKUPS( 'Data.xlsx'  , '2014' , 'A' , 'E4' ))
            ~           1
            ~                       |

DE AT hourly spot=
            DE AT yearly average
            *
            DE AT spot profile
            ~           CHF/(MW*Hour)
            ~                       |

Inflow data 2014(
            GET XLS LOOKUPS( 'Data.xlsx' , '2014' , 'A' , 'M4' ))
            ~           MW*Hour/Hour/(MW*Hour/year)
            ~                       |

Wind factor 2010(
            GET XLS LOOKUPS( 'Data.xlsx'  , '2010' , 'A' , 'O4' ))
            ~           Dmnl
            ~                       |

Demand factor hourly=
            IF THEN ELSE(Profile year = 2010, Demand factor 2010(Lookup Time),
            IF THEN ELSE(Profile year = 2011, Demand factor 2011(Lookup Time),
            IF THEN ELSE(Profile year = 2012, Demand factor 2012(Lookup Time),
            IF THEN ELSE(Profile year = 2013, Demand factor 2013(Lookup Time),
            IF THEN ELSE(Profile year = 2014, Demand factor 2014(Lookup Time),0)))))
            ~           MW/((MW*Hour)/year)
            ~           MW per MWh per year
            |

FR spot 2012(
            GET XLS LOOKUPS( 'Data.xlsx'  , '2012' , 'A' , 'D4' ))
            ~           1
            ~                       |

FR spot 2013(
            GET XLS LOOKUPS( 'Data.xlsx'  , '2010' , 'A' , 'D4' ))
            ~           1
            ~                       |

Solar subsidized capacity=
            Solar approved projects+Solar installed capacity+Solar under construction
            ~           MW
            ~                       |

IT hourly spot=
            IT yearly average
            *
            IT spot profile
            ~           CHF/(MW*Hour)
            ~                       |

Wind factor 2012(
            GET XLS LOOKUPS( 'Data.xlsx'  , '2012' , 'A' , 'O4' ))
```

```
		~	Dmnl
		~		|

IT spot profile=
		IF THEN ELSE(Profile year = 2010, IT spot 2010(Lookup Time),
		IF THEN ELSE(Profile year = 2011, IT spot 2011(Lookup Time),
		IF THEN ELSE(Profile year = 2012, IT spot 2012(Lookup Time),
		IF THEN ELSE(Profile year = 2013, IT spot 2013(Lookup Time),
		IF THEN ELSE(Profile year = 2014, IT spot 2014(Lookup Time),0)))))
		~	Dmnl
		~		|

Solar utilization data(
		GET XLS LOOKUPS( 'Data.xlsx' , 'Solar' , 'A' , 'B4' ))
		~	1
		~		|

Solar utilization factor=
		Solar utilization data(Solar relative installed capacity)
		~	Dmnl
		~		|

Wind factor 2011(
		GET XLS LOOKUPS( 'Data.xlsx'  , '2011' , 'A' , 'O4' ))
		~	Dmnl
		~		|

Solar profitability indicator=
		-Solar investment costs
		+(-Solar annual fixed costs CHF+Solar utilization factor*Hours per year*(-Solar operational costs\
			+Solar selling price))
		/((1+Solar IRR
		)^0)
		+(-Solar annual fixed costs CHF+Solar utilization factor*Hours per year*(-Solar operational costs\
			+Solar selling price))
		/((1+Solar IRR
		)^1)
		+(-Solar annual fixed costs CHF+Solar utilization factor*Hours per year*(-Solar operational costs\
			+Solar selling price))
		/((1+Solar IRR
		)^2)
		+(-Solar annual fixed costs CHF+Solar utilization factor*Hours per year*(-Solar operational costs\
			+Solar selling price))
		/((1+Solar IRR
		)^3)
		+(-Solar annual fixed costs CHF+Solar utilization factor*Hours per year*(-Solar operational costs\
			+Solar selling price forecast 5y
		))/((1+Solar IRR
		)^4)
		+(-Solar annual fixed costs CHF+Solar utilization factor*Hours per year*(-Solar operational costs\
			+Solar selling price forecast 5y
		))/((1+Solar IRR
		)^5)
		+(-Solar annual fixed costs CHF+Solar utilization factor*Hours per year*(-Solar operational costs\
			+Solar selling price forecast 5y
		))/((1+Solar IRR
		)^6)
		+(-Solar annual fixed costs CHF+Solar utilization factor*Hours per year*(-Solar operational costs\
			+Solar selling price forecast 5y
		))/((1+Solar IRR
		)^7)
		+(-Solar annual fixed costs CHF+Solar utilization factor*Hours per year*(-Solar operational costs\
			+Solar selling price forecast 5y
		))/((1+Solar IRR
		)^8)
		+(-Solar annual fixed costs CHF+Solar utilization factor*Hours per year*(-Solar operational costs\
			+Solar selling price forecast 10y
		))/((1+Solar IRR
		)^9)
		+(-Solar annual fixed costs CHF+Solar utilization factor*Hours per year*(-Solar operational costs\
			+Solar selling price forecast 10y
		))/((1+Solar IRR
		)^10)
		+(-Solar annual fixed costs CHF+Solar utilization factor*Hours per year*(-Solar operational costs\
			+Solar selling price forecast 10y
		))/((1+Solar IRR
		)^11)
		+(-Solar annual fixed costs CHF+Solar utilization factor*Hours per year*(-Solar operational costs\
			+Solar selling price forecast 10y
		))/((1+Solar IRR
		)^12)
		+(-Solar annual fixed costs CHF+Solar utilization factor*Hours per year*(-Solar operational costs\
			+Solar selling price forecast 10y
		))/((1+Solar IRR
		)^13)
		+(-Solar annual fixed costs CHF+Solar utilization factor*Hours per year*(-Solar operational costs\
			+Solar selling price forecast 10y
		))/((1+Solar IRR
		)^14)
		+(-Solar annual fixed costs CHF+Solar utilization factor*Hours per year*(-Solar operational costs\
```

```
			+Solar selling price forecast 10y
		))/((1+Solar IRR
		)^15)
		+(-Solar annual fixed costs CHF+Solar utilization factor*Hours per year*(-Solar operational costs\
			+Solar selling price forecast 10y
		))/((1+Solar IRR
		)^16)
		+(-Solar annual fixed costs CHF+Solar utilization factor*Hours per year*(-Solar operational costs\
			+Solar selling price forecast 10y
		))/((1+Solar IRR
		)^17)
		+(-Solar annual fixed costs CHF+Solar utilization factor*Hours per year*(-Solar operational costs\
			+Solar selling price forecast 10y
		))/((1+Solar IRR
		)^18)
		+(-Solar annual fixed costs CHF+Solar utilization factor*Hours per year*(-Solar operational costs\
			+Solar selling price forecast 10y
		))/((1+Solar IRR
		)^19)
		+
		IF THEN ELSE(Option scenario=5,
		+(-Solar annual fixed costs CHF+Solar utilization factor*Hours per year*(-Solar operational costs\
			+Solar selling price forecast 10y
		))/((1+Solar IRR
		)^20)
		+(-Solar annual fixed costs CHF+Solar utilization factor*Hours per year*(-Solar operational costs\
			+Solar selling price forecast 10y
		))/((1+Solar IRR
		)^21)
		+(-Solar annual fixed costs CHF+Solar utilization factor*Hours per year*(-Solar operational costs\
			+Solar selling price forecast 10y
		))/((1+Solar IRR
		)^22)
		+(-Solar annual fixed costs CHF+Solar utilization factor*Hours per year*(-Solar operational costs\
			+Solar selling price forecast 10y
		))/((1+Solar IRR
		)^23)
		+(-Solar annual fixed costs CHF+Solar utilization factor*Hours per year*(-Solar operational costs\
			+Solar selling price forecast 10y
		))/((1+Solar IRR
		)^24),0)
	~	CHF/MW
	~	Economic lifetime of 20y from Poyry (2012)
	|

Inflow data 2012(
	GET XLS LOOKUPS( 'Data.xlsx' , '2012' , 'A' , 'M4' ))
	~	MW*Hour/Hour/(MW*Hour/year)
	~		|

Wind factor hourly=
	IF THEN ELSE(Profile year = 2010, Wind factor 2010(Lookup Time),
	IF THEN ELSE(Profile year = 2011, Wind factor 2011(Lookup Time),
	IF THEN ELSE(Profile year = 2012, Wind factor 2012(Lookup Time),
	IF THEN ELSE(Profile year = 2013, Wind factor 2013(Lookup Time),
	IF THEN ELSE(Profile year = 2014, Wind factor 2014(Lookup Time),0)))))
	~	Dmnl
	~		|

Hydro hourly inflow factor=
	IF THEN ELSE(Profile year = 2010, Inflow data 2010(Lookup Time),
	IF THEN ELSE(Profile year = 2011, Inflow data 2011(Lookup Time),
	IF THEN ELSE(Profile year = 2012, Inflow data 2012(Lookup Time),
	IF THEN ELSE(Profile year = 2013, Inflow data 2013(Lookup Time),
	IF THEN ELSE(Profile year = 2014, Inflow data 2014(Lookup Time),0)))))
	~	MW*Hour/Hour/(MW*Hour/year)
	~	% of yearly inflow; or
		MWh per hour (MW) per MWh/year
	|

Wind factor 2014(
	GET XLS LOOKUPS( 'Data.xlsx'  , '2014' , 'A' , 'O4' ))
	~	Dmnl
	~		|

Inflow data 2013(
	GET XLS LOOKUPS( 'Data.xlsx' , '2013' , 'A' , 'M4' ))
	~	MW*Hour/Hour/(MW*Hour/year)
	~		|

Wind relative installed capacity=
	Wind installed capacity/Maximum theoretical wind capacity
	~	1
	~		|

IT spot 2013(
	GET XLS LOOKUPS( 'Data.xlsx'  , '2013' , 'A' , 'E4' ))
	~	1
	~		|
```

```
Wind factor 2013(
		GET XLS LOOKUPS( 'Data.xlsx'  , '2013' , 'A' , 'O4' ))
		~		Dmnl
		~				|

Relative reservoir capacity=
		(Hydropower reservoir)/Max regular reservoir capacity
		~		Dmnl
		~				|

Demand factor 2010(
		GET XLS LOOKUPS( 'Data.xlsx'  , '2010' , 'A' , 'B4' ))
		~		MW/((MW*Hour)/year)
		~				|

Demand factor 2011(
		GET XLS LOOKUPS( 'Data.xlsx'  , '2011' , 'A' , 'B4' ))
		~		MW/((MW*Hour)/year)
		~				|

Demand factor 2012(
		GET XLS LOOKUPS( 'Data.xlsx'  , '2012' , 'A' , 'B4' ))
		~		MW/((MW*Hour)/year)
		~				|

Demand factor 2013(
		GET XLS LOOKUPS( 'Data.xlsx'  , '2013' , 'A' , 'B4' ))
		~		MW/((MW*Hour)/year)
		~				|

Demand factor 2014(
		GET XLS LOOKUPS( 'Data.xlsx'  , '2014' , 'A' , 'B4' ))
		~		MW/((MW*Hour)/year)
		~				|

Profile year=
		2010
		~		1
		~		Range between 2010-2014, no decimals.
		|

Relative pumped capacity=
		Hydropower pumped reservoir/Max pumped reservoir capacity
		~		1
		~				|

Hydro pumped opportunity cost=
		MIN(MAX(((1-Relative pumped capacity)*(3*Spot price yearly average-0.95*Lowest foreign average price\
			))+0.95*Lowest foreign average price,0),150)
		~		CHF/(MW*Hour)
		~				|

PV year=
		2000
		~		1
		~		Range between 1996-2000, no decimals.
		|

Wind hurdle rate=
		IF THEN ELSE(Option scenario=5,0.09,0.11)
		~		Dmnl
		~		Poyry
		|

CCGT hurdle rate=
		IF THEN ELSE(Option scenario=5,0.07,0.09)
		~		Dmnl
		~		Poyry 2012
		|

Price floor=
		IF THEN ELSE(Option scenario=3,10,0)
		~		CHF/(MW*Hour)
		~				|

Option scenario=
		1
		~		Dmnl
		~		1=BAU, 2=DPO (do not use), 3=PF, 4=FCE, 5=LIB
		|

Subsidy year stop=
		IF THEN ELSE(Option scenario=4,2025,2035)
		~		Hour
		~		From Osorio 2016
				Units have to be same as Time (Hour) but model accepts actual year numbes
		|

Wind profitability indicator=
		(-Wind investment costs
```

```
        +(-Wind annual fixed costs+0.23*Hours per year*(-Wind operational costs+Wind selling price\
                ))/((1+Wind IRR)^0)
        +(-Wind annual fixed costs+0.23*Hours per year*(-Wind operational costs+Wind selling price\
                ))/((1+Wind IRR)^1)
        +(-Wind annual fixed costs+0.23*Hours per year*(-Wind operational costs+Wind selling price\
                ))/((1+Wind IRR)^2)
        +(-Wind annual fixed costs+0.23*Hours per year*(-Wind operational costs+Wind selling price\
                ))/((1+Wind IRR)^3)
        +(-Wind annual fixed costs+0.23*Hours per year*(-Wind operational costs+Wind selling price forecast 5y\
                ))/((1+Wind IRR)^
        4)
        +(-Wind annual fixed costs+0.23*Hours per year*(-Wind operational costs+Wind selling price forecast 5y\
                ))/((1+Wind IRR)^
        5)
        +(-Wind annual fixed costs+0.23*Hours per year*(-Wind operational costs+Wind selling price forecast 5y\
                ))/((1+Wind IRR)^
        6)
        +(-Wind annual fixed costs+0.23*Hours per year*(-Wind operational costs+Wind selling price forecast 5y\
                ))/((1+Wind IRR)^
        7)
        +(-Wind annual fixed costs+0.23*Hours per year*(-Wind operational costs+Wind selling price forecast 5y\
                ))/((1+Wind IRR)^
        8)
        +(-Wind annual fixed costs+0.23*Hours per year*(-Wind operational costs+Wind selling price forecast 5y\
                ))/((1+Wind IRR)^
        9)
        +(-Wind annual fixed costs+0.23*Hours per year*(-Wind operational costs+Wind selling price forecast 10y\
                ))/((1+Wind IRR)
        ^10)
        +(-Wind annual fixed costs+0.23*Hours per year*(-Wind operational costs+Wind selling price forecast 10y\
                ))/((1+Wind IRR)
        ^11)
        +(-Wind annual fixed costs+0.23*Hours per year*(-Wind operational costs+Wind selling price forecast 10y\
                ))/((1+Wind IRR)
        ^12)
        +(-Wind annual fixed costs+0.23*Hours per year*(-Wind operational costs+Wind selling price forecast 10y\
                ))/((1+Wind IRR)
        ^13)
        +(-Wind annual fixed costs+0.23*Hours per year*(-Wind operational costs+Wind selling price forecast 10y\
                ))/((1+Wind IRR)
        ^14)
        +(-Wind annual fixed costs+0.23*Hours per year*(-Wind operational costs+Wind selling price forecast 10y\
                ))/((1+Wind IRR)
        ^15)
        +(-Wind annual fixed costs+0.23*Hours per year*(-Wind operational costs+Wind selling price forecast 10y\
                ))/((1+Wind IRR)
        ^16)
        +(-Wind annual fixed costs+0.23*Hours per year*(-Wind operational costs+Wind selling price forecast 10y\
                ))/((1+Wind IRR)
        ^17)
        +(-Wind annual fixed costs+0.23*Hours per year*(-Wind operational costs+Wind selling price forecast 10y\
                ))/((1+Wind IRR)
        ^18)
        +(-Wind annual fixed costs+0.23*Hours per year*(-Wind operational costs+Wind selling price forecast 10y\
                ))/((1+Wind IRR)
        ^19))
        +IF THEN ELSE(Option scenario=5,
        +(-Wind annual fixed costs+0.23*Hours per year*(-Wind operational costs+Wind selling price forecast 10y\
                ))/((1+Wind IRR)
        ^20)
        +(-Wind annual fixed costs+0.23*Hours per year*(-Wind operational costs+Wind selling price forecast 10y\
                ))/((1+Wind IRR)
        ^21)
        +(-Wind annual fixed costs+0.23*Hours per year*(-Wind operational costs+Wind selling price forecast 10y\
                ))/((1+Wind IRR)
        ^22)
        +(-Wind annual fixed costs+0.23*Hours per year*(-Wind operational costs+Wind selling price forecast 10y\
                ))/((1+Wind IRR)
        ^23)
        +(-Wind annual fixed costs+0.23*Hours per year*(-Wind operational costs+Wind selling price forecast 10y\
                ))/((1+Wind IRR)
        ^24),0)
        ~       CHF/MW
        ~       20y economic lifetime from Poyry 2012
        |

CCGT profitability indicator=
        -CCGT investment costs
        +(-CCGT annual fixed costs+CCGT utilization factor*Hours per year*(-CCGT operational costs\
                +CCGT selling price))/((1+CCGT IRR
        )^0)
        +(-CCGT annual fixed costs+CCGT utilization factor*Hours per year*(-CCGT operational costs\
                +CCGT selling price))/((1+CCGT IRR
        )^1)
        +(-CCGT annual fixed costs+CCGT utilization factor*Hours per year*(-CCGT operational costs\
                +CCGT selling price))/((1+CCGT IRR
        )^2)
        +(-CCGT annual fixed costs+CCGT utilization factor*Hours per year*(-CCGT operational costs\
                +CCGT selling price))/((1+CCGT IRR
        )^3)
```

```
	+(-CCGT annual fixed costs+CCGT utilization factor*Hours per year*(-CCGT operational costs forecast 5y\
		+CCGT selling price forecast 5y
	))/((1+CCGT IRR)^4)
	+(-CCGT annual fixed costs+CCGT utilization factor*Hours per year*(-CCGT operational costs forecast 5y\
		+CCGT selling price forecast 5y
	))/((1+CCGT IRR)^5)
	+(-CCGT annual fixed costs+CCGT utilization factor*Hours per year*(-CCGT operational costs forecast 5y\
		+CCGT selling price forecast 5y
	))/((1+CCGT IRR)^6)
	+(-CCGT annual fixed costs+CCGT utilization factor*Hours per year*(-CCGT operational costs forecast 5y\
		+CCGT selling price forecast 5y
	))/((1+CCGT IRR)^7)
	+(-CCGT annual fixed costs+CCGT utilization factor*Hours per year*(-CCGT operational costs forecast 5y\
		+CCGT selling price forecast 5y
	))/((1+CCGT IRR)^8)
	+(-CCGT annual fixed costs+CCGT utilization factor*Hours per year*(-CCGT operational costs forecast 10y\
		+CCGT selling price forecast 10y
	))/((1+CCGT IRR)^9)
	+(-CCGT annual fixed costs+CCGT utilization factor*Hours per year*(-CCGT operational costs forecast 10y\
		+CCGT selling price forecast 10y
	))/((1+CCGT IRR)^10
	)
	+(-CCGT annual fixed costs+CCGT utilization factor*Hours per year*(-CCGT operational costs forecast 10y\
		+CCGT selling price forecast 10y
	))/((1+CCGT IRR)^11
	)
	+(-CCGT annual fixed costs+CCGT utilization factor*Hours per year*(-CCGT operational costs forecast 10y\
		+CCGT selling price forecast 10y
	))/((1+CCGT IRR)^12
	)
	+(-CCGT annual fixed costs+CCGT utilization factor*Hours per year*(-CCGT operational costs forecast 10y\
		+CCGT selling price forecast 10y
	))/((1+CCGT IRR)^13
	)
	+(-CCGT annual fixed costs+CCGT utilization factor*Hours per year*(-CCGT operational costs forecast 10y\
		+CCGT selling price forecast 10y
	))/((1+CCGT IRR)^14
	)
	+(-CCGT annual fixed costs+CCGT utilization factor*Hours per year*(-CCGT operational costs forecast 10y\
		+CCGT selling price forecast 10y
	))/((1+CCGT IRR)^15
	)
	+(-CCGT annual fixed costs+CCGT utilization factor*Hours per year*(-CCGT operational costs forecast 10y\
		+CCGT selling price forecast 10y
	))/((1+CCGT IRR)^16
	)
	+(-CCGT annual fixed costs+CCGT utilization factor*Hours per year*(-CCGT operational costs forecast 10y\
		+CCGT selling price forecast 10y
	))/((1+CCGT IRR)^17
	)
	+(-CCGT annual fixed costs+CCGT utilization factor*Hours per year*(-CCGT operational costs forecast 10y\
		+CCGT selling price forecast 10y
	))/((1+CCGT IRR)^18
	)
	+(-CCGT annual fixed costs+CCGT utilization factor*Hours per year*(-CCGT operational costs forecast 10y\
		+CCGT selling price forecast 10y
	))/((1+CCGT IRR)^19
	)
	+IF THEN ELSE(Option scenario=5,
	+(-CCGT annual fixed costs+CCGT utilization factor*Hours per year*(-CCGT operational costs forecast 10y\
		+CCGT selling price forecast 10y
	))/((1+CCGT IRR)^20
	)
	+(-CCGT annual fixed costs+CCGT utilization factor*Hours per year*(-CCGT operational costs forecast 10y\
		+CCGT selling price forecast 10y
	))/((1+CCGT IRR)^21
	)
	+(-CCGT annual fixed costs+CCGT utilization factor*Hours per year*(-CCGT operational costs forecast 10y\
		+CCGT selling price forecast 10y
	))/((1+CCGT IRR)^22
	)
	+(-CCGT annual fixed costs+CCGT utilization factor*Hours per year*(-CCGT operational costs forecast 10y\
		+CCGT selling price forecast 10y
	))/((1+CCGT IRR)^23
	)
	+(-CCGT annual fixed costs+CCGT utilization factor*Hours per year*(-CCGT operational costs forecast 10y\
		+CCGT selling price forecast 10y
	))/((1+CCGT IRR)^24
	),0)
	~	CHF/MW
	~	Economic lifetime 20 years from Poyry, 2012
	|

Solar hurdle rate=
	IF THEN ELSE(Option scenario=5,0.1,0.12)
	~	Dmnl
	~	Poyry (2012)
	|

Nuclear installed capacity= INTEG (
```

```
        -Nuclear phaseout,
                3278)
        ~       MW
        ~               |

Year subsidy stop=
        IF THEN ELSE(Option scenario=4,2025,2035)
        ~       Hour
        ~       Found in Van Ackere (2016) as 2035, can play around
                Unit has to be in same unit as Time unit (but the model accepts actual \
                years)
        |

CCGT cumulative marginal producer= INTEG (
        IF THEN ELSE(CCGT price=Spot price,1,0)-IF THEN ELSE(Year end=1,CCGT cumulative marginal producer\
                *C,0),
                0)
        ~       Hour
        ~               |

CCGT marginal producer rate yearly=
        SAMPLE IF TRUE(Year end=1,ZIDZ(CCGT cumulative marginal producer,Hours per year), 0.1\
                )
        ~       Dmnl
        ~               |

Yearly imports= INTEG (
        FR import contracts amount+IF THEN ELSE("Net import/export balance">0,"Net import/export balance"\
                ,0)-IF THEN ELSE(Year end=1,Yearly imports*C,0),
                0)
        ~       MW*Hour
        ~               |

"Net import/export balance"=
        SIMULTANEOUS((DE AT balance+FR balance+IT balance),0)
        ~       MW
        ~       Positive if importing, negative if exporting
        |

Spot price cumulative seasonal= INTEG (
        Spot price*Swiss hourly electricity demand-IF THEN ELSE(Season end=1,Spot price cumulative seasonal\
                *C,0),
                0)
        ~       CHF
        ~               |

Demand counter= INTEG (
        Swiss hourly electricity demand-IF THEN ELSE(Season end=1,Demand counter*C,0),
                0)
        ~       MW*Hour
        ~               |

Spot price seasonal sampling=
        SAMPLE IF TRUE(Season end=1,ZIDZ(Spot price cumulative seasonal,Demand counter),75)
        ~       CHF/(MW*Hour)
        ~       Remembered: delay by 1 season; i.e. during summer this variable gives the spring \
                value.
                Weighted by the actual volumes traded!
        |

Price spread seasonal=
        SAMPLE IF TRUE(Season end=1,ZIDZ(Price spread counter,Hours per season),1)
        ~       1
        ~               |

Price spread counter= INTEG (
        Price spread daily-IF THEN ELSE(Season end=1,Price spread counter*C,0),
                0)
        ~       Hour
        ~               |

Nuclear available capacity=
        Nuclear seasonal availability(Season)*Nuclear installed capacity
        ~       MW
        ~       Data on phaseout from SFOE Osorio, 2016
        |

NTC usage=
        0.25
        ~       Dmnl
        ~               |

Nuclear seasonal availability(
        [(1,0)-(4,1)],(1,1),(2,0.89),(3,0.7),(4,0.89))
        ~       Dmnl
        ~               |

IT yearly average=
        IF THEN ELSE(Spot price scenario = 1, IT S1(Year),
        IF THEN ELSE(Spot price scenario = 2, IT S2(Year),
```

```
        0 ) )
        * EUR to CHF
        ~       CHF/(MW*Hour)
        ~               |

DE AT yearly average=
        IF THEN ELSE(Spot price scenario = 1, DE AT S1(Year),
        IF THEN ELSE(Spot price scenario = 2, DE AT S2(Year),
        0 ) )
        * EUR to CHF
        ~       CHF/(MW*Hour)
        ~               |

FR yearly average=
        IF THEN ELSE(Spot price scenario = 1, FR S1(Year),
        IF THEN ELSE(Spot price scenario = 2, FR S2(Year),
        0 ) )
        * EUR to CHF
        ~       CHF/(MW*Hour)
        ~               |

Hydropower pumping= ACTIVE INITIAL (
        Hydropower pumping amount,
                0)
        ~       MW
        ~       "Bang-Bang" pumping regime leads to optimal profits in many optimization models \
                according to Densing (2013).
                Pumping decisions are done by firms that traditionally use optimization, \
                so using "bang-bang" is the appropriate way to model.
        |

Lowest foreign average price=
        MIN(MIN(DE AT yearly average,FR yearly average),IT yearly average)
        ~       CHF/(MW*Hour)
        ~               |

Solar selling price=
        SAMPLE IF TRUE(Year end=1,ZIDZ(Solar yearly price sum,Solar production counter),50)
        ~       CHF/(MW*Hour)
        ~               |

CCGT utilization factor=
        SAMPLE IF TRUE(Year end=1,XIDZ(CCGT cumulative production,CCGT installed capacity*Hours per year\
                ,0), 0.9)
        ~       Dmnl [0,1]
        ~               |

Overflow pumped=
        IF THEN ELSE(Hydropower pumped reservoir>=Max pumped reservoir capacity,MAX(0,C*(Hydropower pumped reservoir\
                -Max pumped reservoir capacity)),0)
        ~       (MW*Hour)/Hour
        ~               |

CCGT production counter= INTEG (
        CCGT production-IF THEN ELSE(Year end=1,CCGT production counter*C,0),
                1)
        ~       MW*Hour
        ~               |

Max pumped reservoir capacity=
        Max reservoir capacity*Hydropower capacity ratio pumping
        ~       MW*Hour
        ~               |

Max regular reservoir capacity=
        (1-Hydropower capacity ratio pumping)*Max reservoir capacity
        ~       MW*Hour
        ~               |

Wind selling price=
        SAMPLE IF TRUE(Year end=1,ZIDZ(Wind yearly price sum,Wind production counter),ZIDZ(Wind yearly price sum\
                ,Wind production counter
))
        ~       CHF/(MW*Hour)
        ~       Wind price used in investments, averaged received price for wind \
                production in the previous year
        |

Hydropower pumped reservoir= INTEG (
        Hydropower pumping+Inflow pumped hourly-Hydropower pumped production-Overflow pumped\
                ,
                1.20552e+06)
        ~       MW*Hour
        ~       For initial value, see regular reservoir
        |

Solar production counter= INTEG (
        Solar production-IF THEN ELSE(Year end=1,Solar production counter*C,0),
                1)
        ~       MW*Hour
```

```
	~		|

CCGT application decision=
	IF THEN ELSE(Year end=1:AND:CCGT IRR>CCGT hurdle rate,CCGT average size,0)
	~	MW/Hour
	~		|

Hydropower reservoir= INTEG (
	Inflow regular hourly-Hydropower reservoir production-Overflow regular,
		4.30548e+06)
	~	MW*Hour
	~	5510000 = at start = 63% full
		Capacity ratio at start = 1800/8234, so we need 1205518 and 4305482 in \
		pumped/reg, respectively, at start.
	|

Wind project application rate=
	IF THEN ELSE(Year end=1:AND:Wind IRR>Wind hurdle rate,Wind average size,0)
	~	MW/Hour
	~		|

Wind unprofitable year count= INTEG (
	IF THEN ELSE(Year end=1:AND:Wind IRR<Wind hurdle rate,1,0)-IF THEN ELSE(Wind IRR>Wind hurdle rate\
		,Wind unprofitable year count
*C,0),
		0)
	~	Hour
	~		|

Inflow pumped hourly=
	Hydro hourly inflow factor*Hydro yearly inflow*Hydropower capacity ratio pumping
	~	(MW*Hour)/Hour
	~		|

Solar unprofitable year count= INTEG (
	IF THEN ELSE(Year end=1:AND:Solar IRR<Solar hurdle rate,1,0)-IF THEN ELSE(Solar IRR>\
		Solar hurdle rate,Solar unprofitable year count
*C,0),
		0)
	~	Hour
	~		|

CCGT selling price=
	SAMPLE IF TRUE(Year end=1,ZIDZ(CCGT yearly price sum,CCGT production counter),ZIDZ(CCGT yearly price sum\
		,CCGT production counter
))
	~	CHF/(MW*Hour)
	~		|

Solar yearly price sum= INTEG (
	Solar production*Spot price forecast-IF THEN ELSE(Year end=1,Solar yearly price sum*\
		C,0),
		0)
	~	CHF
	~		|

CCGT cumulative production= INTEG (
	CCGT production-IF THEN ELSE(Year end=1,CCGT cumulative production*C,0),
		0)
	~	MW*Hour
	~		|

Yearly exports= INTEG (
	IF THEN ELSE("Net import/export balance"<0,"Net import/export balance",0)-IF THEN ELSE\
		(Year end=1,Yearly exports*C,0),
		0)
	~	MW*Hour
	~		|

Wind yearly price sum= INTEG (
	Spot price forecast*Wind production-IF THEN ELSE( Year end=1 , Wind yearly price sum\
		*C , 0 ),
		30)
	~	CHF
	~		|

Peak demand= INTEG (
	IF THEN ELSE(Swiss hourly electricity demand>Peak demand,Swiss hourly electricity demand\
		*C-Peak demand*C,0)-IF THEN ELSE
(Year end=1,Peak demand*C,0),
		8000)
	~	MW
	~	Memory of 1 year, peak demand
	|

Overflow regular=
	IF THEN ELSE(Hydropower reservoir>=Max regular reservoir capacity,MAX(0,C*(Hydropower reservoir\
		-Max regular reservoir capacity)),0)
	~	(MW*Hour)/Hour
	~		|
```

```
Wind production counter= INTEG (
        Wind production-IF THEN ELSE(Year end=1,Wind production counter*C,0),
                1)
        ~       MW*Hour
        ~               |

Pumping efficiency=
        0.8
        ~       Dmnl
        ~               |

Yearly imports net=
        SAMPLE IF TRUE(Year end=1,Yearly imports+Yearly exports, Yearly imports+Yearly exports\
                )
        ~       MW*Hour
        ~               |

Inflow regular hourly=
        Hydro yearly inflow*Hydro hourly inflow factor*(1-Hydropower capacity ratio pumping)
        ~       (MW*Hour)/Hour
        ~       OLD: 2*Hydro availability factor*Max reservoir capacity/120
                Inflow depends on the hydrological regime (availability factor) and on the max \
                reservoir capacity, which is also in a way a proxy for the catchment size.
                Generally, around 37-40 TWh of hydro per year (2012/2013: 39'631 GWh), of which 55% \
                from hydro storage, meaning the reservoir capacity (of around 300 GWh) \
                flows in every 24*365/(0,55*37'000 to 40'000/300)=120 to 130 hours (swiss \
                electricity statistics)
                Poyry (2012) assumes 18.8 TWh per year flows in, or max capacity of 0.2976 gets \
                replenished 63.17 times or every 138 hours (on average)
                Factor of 2 is because the availability factor averages to 0.5 and not to \
                0.1
        |

CCGT yearly price sum= INTEG (
        Spot price forecast*CCGT production-IF THEN ELSE(Year end=1,CCGT yearly price sum*C,\
                0),
                30)
        ~       CHF
        ~               |

Hydropower maximum capacity=
        9920+1000*STEP(1,(2016-2015)*8760)+900*STEP(1,(2018-2015)*8760)
        ~       MW
        ~               |

Residual demand=
        SIMULTANEOUS(
        MAX(((1+Transmission losses)*Swiss hourly electricity demand)+Hydropower pumping amount\
                -Total VRES production-"Net import/export balance",0)
        ,0)
        ~       MW
        ~               |

Spot price base= INTEG (
        IF THEN ELSE(Hour=2,Spot price,0)*C+IF THEN ELSE(Hour>2:AND:Spot price<Spot price base\
                ,Spot price-Spot price base,0)*C-IF THEN ELSE(Hour=1,Spot price base,0)*C,
                0)
        ~       CHF/(MW*Hour)
        ~               |

Price spread daily=
        SAMPLE IF TRUE(Hour=1,XIDZ(Spot price peak,Spot price base,1),1)
        ~       Dmnl
        ~       Daily ratio peak / off-peak price
        |

Spot price peak= INTEG (
        IF THEN ELSE(Spot price>Spot price peak,Spot price-Spot price peak,0)*C-IF THEN ELSE\
                (Hour=1,Spot price peak,0)*C,
                0)
        ~       CHF/(MW*Hour)
        ~               |

Hours per month=
        730
        ~       Hour
        ~               |

SD price volatility=
        SAMPLE IF TRUE(Month end=1,SQRT(SD counter/Hours per month),0)
        ~       CHF/(MW*Hour)
        ~       Monthly calculated standard deviation; 2 month lag in the timing!
        |

Spot price monthly delay=
        DELAY FIXED(Spot price,730,0)
        ~       CHF/(MW*Hour)
        ~               |
```

```
Spot price cumulative monthly= INTEG (
		Spot price-IF THEN ELSE(Month end=1,Spot price cumulative monthly*C,0),
			0)
		~		Hour*CHF/(MW*Hour)
		~			|

SD counter= INTEG (
		(Spot price monthly mean-Spot price monthly delay)^2-IF THEN ELSE(Month end=1,SD counter\
			*C,0),
			0)
		~		CHF*CHF/(MW*MW*Hour)
		~			|

Spot price monthly mean=
		SAMPLE IF TRUE(Month end=1,Spot price cumulative monthly/Hours per month,0)
		~		CHF/(MW*Hour)
		~			|

Month end=
		IF THEN ELSE(MODULO(Time,730)=0:AND:Time>0,1,0)
		~		Dmnl
		~			|

FR import contract maximum = WITH LOOKUP (
		Year,
			([(2014,0)-(2050,4000)],(2014,2688),(2020,1920),(2025,1664),(2030,1407),(2035,640),\
			(2040,0),(2050,0) ))
		~		MW
		~		AES/VSE 2012
		|

FR import contract=
		MIN(FR hourly import NTC,FR import contract maximum)
		~		MW
		~			|

CCGT selling price trend=
		SMOOTH(CCGT selling price,0.5*Hours per year)
		~		CHF/(MW*Hour)
		~			|

Wind selling price forecast 10y=
		FORECAST( Wind selling price trend , 3*Hours per year , 10*Hours per year )
		~		CHF/(MW*Hour)
		~			|

Wind selling price forecast 5y=
		FORECAST( Wind selling price trend , 3*Hours per year , 5*Hours per year )
		~		CHF/(MW*Hour)
		~			|

Solar selling price forecast 10y=
		FORECAST( Solar selling price trend , 3*Hours per year , 10*Hours per year )
		~		CHF/(MW*Hour)
		~			|

Solar selling price forecast 5y=
		FORECAST( Solar selling price trend , 3*Hours per year , 5*Hours per year )
		~		CHF/(MW*Hour)
		~			|

Solar selling price trend=
		SMOOTH(Solar selling price,0.5*Hours per year)
		~		CHF/(MW*Hour)
		~			|

CCGT selling price forecast 10y=
		MAX(0,FORECAST( CCGT selling price trend , 3*Hours per year , 10*Hours per year ))
		~		CHF/(MW*Hour)
		~			|

CCGT selling price forecast 5y=
		MAX(0,FORECAST( CCGT selling price trend , 3*Hours per year , 5*Hours per year ))
		~		CHF/(MW*Hour)
		~			|

Wind selling price trend=
		SMOOTH(Wind selling price,0.5*Hours per year)
		~		CHF/(MW*Hour)
		~			|

Energy security seasonal=
		SAMPLE IF TRUE(Season end=1,Spot price stable counter/Hours per season,1)
		~		Dmnl [0,1]
		~		Percentage of time the grid is stable (i.e. no lost load). Often has to be \
			>0.99 in country regulations.
		|

Demand yearly=
		IF THEN ELSE( VSE SCENARIO = 1, Demand VSE1(Year),
```

```
        IF THEN ELSE( VSE SCENARIO = 2, Demand VSE2(Year),
        IF THEN ELSE( VSE SCENARIO = 3, Demand VSE3(Year),
        0))) * TWh to MWh
        ~       MW*Hour/year
        ~               |

Wind permitting time=
        1/12*Hours per year
        ~       Hour
        ~               |

CCGT operational costs forecast 5y=
        FORECAST(CCGT operational costs,3*Hours per year,5*Hours per year)
        ~       CHF/(MW*Hour)
        ~               |

CCGT operational costs forecast 10y=
        FORECAST(CCGT operational costs,3*Hours per year,10*Hours per year)
        ~       CHF/(MW*Hour)
        ~               |

Social acceptance=
        MIN((Wind installed capacity increasing/Maximum theoretical wind capacity)/2+(1-Proximity to community\
                )/2,1)
        ~       Dmnl
        ~               |

"Net import/export balance forecast"=
        MIN(MAX(FORECAST("Net import/export balance",3*Hours per year,1/C),-7500),7500)
        ~       MW
        ~       Short forecast, but using the average trend over the last few years to \
                make a decision about the current situation
        |

Wind application approval rate=
        IF THEN ELSE(Wind application delay>0,MAX(Wind in permitting process*C,Wind application delay\
                ),0)
        ~       MW/Hour
        ~               |

Solar IRR= INTEG (
        IF THEN ELSE(Solar profitability indicator>0,+0.001*C,-0.001*C)+IF THEN ELSE(Solar IRR\
                <-0.9,0.002*C,0*C)+IF THEN ELSE(Solar IRR
        >0.9,-0.002*C,0*C),
                0)
        ~       Dmnl
        ~               |

Hours per season=
        2190
        ~       Hour
        ~               |

Other thermal installed capacity= INTEG (
        -Other thermal installed capacity/(20*Hours per year),
                542)
        ~       MW
        ~       See master file for explanation
        |

ROR yearly production=
        IF THEN ELSE( VSE SCENARIO = 1, ROR VSE1(Year),
        IF THEN ELSE( VSE SCENARIO = 2, ROR VSE2(Year),
        IF THEN ELSE( VSE SCENARIO = 3, ROR VSE3(Year),
        0))) *TWh to MWh
        ~       (MW*Hour)/year
        ~               |

TWh to MWh=
        1e+06
        ~       MW*Hour/TWh
        ~               |

Hydro yearly inflow=
        IF THEN ELSE( VSE SCENARIO = 1, Yearly inflow VSE1(Year),
        IF THEN ELSE( VSE SCENARIO = 2, Yearly inflow VSE2(Year),
        IF THEN ELSE( VSE SCENARIO = 3, Yearly inflow VSE3(Year),
        0))) * TWh to MWh
        ~       (MW*Hour)/year
        ~               |

Spot price stable counter= INTEG (
        IF THEN ELSE(Spot price<2900,1,0)-IF THEN ELSE(Season end=1,Spot price stable counter\
                *C,0),
                0)
        ~       Hour
        ~               |

Solar project abandoning rate=
        IF THEN ELSE(Solar unprofitable year count>5,Solar approved projects*0.5*C,0)
```

```
        ~       MW/Hour
        ~               |

Wind investment decision=
        IF THEN ELSE(Wind IRR>Wind hurdle rate,Wind approved projects*C,0)
        ~       MW/Hour
        ~               |

Wind investment costs=
        (Wind initial investment costs*(1-(Wind investment subsidies-STEP(Wind investment subsidies\
                ,(Year subsidy stop-Year simulation start
        )*8760
        ))))
        ~       CHF/MW
        ~               |

Solar investment decision=
        IF THEN ELSE(Solar approved projects>0:AND:Solar IRR>Solar hurdle rate,Solar approved projects\
                *C,0)
        ~       MW/Hour
        ~               |

Wind IRR= INTEG (
        IF THEN ELSE(Wind profitability indicator>0,+0.001*C,-0.001*C)+IF THEN ELSE(Wind IRR\
                <-0.9,0.002*C,0*C)+IF THEN ELSE(Wind IRR>0.9,-0.002*C,0*C),
                0)
        ~       Dmnl
        ~               |

Wind application rejection rate=
        IF THEN ELSE(Land scarcity>0.5:AND:Social response>0.5,(Land scarcity+Social response\
                )/2*Wind in permitting process*C,
        IF THEN ELSE(Social response>0.5,Social response*Wind in permitting process*C,
        IF THEN ELSE(Land scarcity>0.5,Land scarcity*Wind in permitting process*C,0)))
        ~       MW/Hour
        ~               |

Wind project abandoning rate=
        IF THEN ELSE(Wind unprofitable year count>5,Wind approved projects*0.5*C,0)
        ~       MW/Hour
        ~               |

Year simulation start=
        2015
        ~       Hour
        ~               |

C=
        1
        ~       1/Hour
        ~       Constant to allow a single time period deduction or addition from an \
                integration variable without causing unit conflict
        |

CCGT IRR= INTEG (
        IF THEN ELSE(CCGT profitability indicator>0,+0.001*C,-0.001*C)+IF THEN ELSE(CCGT IRR\
                <-0.9,0.002*C,0*C)+IF THEN ELSE(CCGT IRR>0.9
        ,-0.002*C,0*C),
                0)
        ~       Dmnl
        ~               |

Available land=
        (Maximum theoretical wind capacity-Wind subsidized capacity)/Maximum theoretical wind capacity
        ~       Dmnl
        ~       2282 is maximum according to Osorio (2016)
        |

Maximum theoretical wind capacity=
        2282
        ~       MW
        ~       in MW, according to Osorio (2016)
        |

Hours per year=
        8760
        ~       Hour
        ~               |

"CCGT O&M EUR"=
        2.4
        ~       EUR/(MW*Hour)
        ~               |

"CCGT O&M"=
        "CCGT O&M EUR"*EUR to CHF
        ~       CHF/(MW*Hour)
        ~       From Poyry 2012, in EUR/MWh, conversion factor 1.09 (Google, 29 March 2016)
        |
```

```
Spot price yearly average=
        (Fall spot price+Spring spot price+Summer spot price+Winter spot price)/4
        ~       CHF/(MW*Hour)
        ~               |

Wind production=
        Wind hourly production factor*Wind installed capacity
        ~       MW
        ~               |

IT S1(
        GET XLS LOOKUPS( 'Data.xlsx'  , 'Scenarios' , 'A' , 'S4' ))
        ~       EUR/(MW*Hour)
        ~               |

IT S2(
        GET XLS LOOKUPS( 'Data.xlsx'  , 'Scenarios' , 'A' , 'T4' ))
        ~       EUR/(MW*Hour)
        ~               |

FR S1(
        GET XLS LOOKUPS( 'Data.xlsx'  , 'Scenarios' , 'A' , 'Q4' ))
        ~       EUR/(MW*Hour)
        ~               |

FR S2(
        GET XLS LOOKUPS( 'Data.xlsx'  , 'Scenarios' , 'A' , 'R4' ))
        ~       EUR/(MW*Hour)
        ~               |

Spot price scenario=
        2
        ~       Dmnl
        ~       1=low, 2=high
                From TYNDP (1=1+2, 2=3+4)
        |

DE AT S1(
        GET XLS LOOKUPS( 'Data.xlsx'  , 'Scenarios' , 'A' , 'O4' ))
        ~       EUR/(MW*Hour)
        ~               |

DE AT S2(
        GET XLS LOOKUPS( 'Data.xlsx'  , 'Scenarios' , 'A' , 'P4' ))
        ~       EUR/(MW*Hour)
        ~               |

ROR VSE3(
        [(0,0)-(3000,20)],(2014,16.7),(2015,16.7),(2020,17.2),(2025,17.6),(2035,18.6),(2050,\
                20))
        ~       TWh/year
        ~               |

ROR production=
        ROR yearly production*ROR hourly production factor
        ~       MW
        ~               |

ROR VSE1(
        [(2014,15)-(2050,25)],(2014,16.2),(2015,16.2),(2020,16.3),(2025,16.4),(2035,16.7),(2050\
                ,17))
        ~       TWh/year
        ~               |

ROR VSE2(
        [(0,0)-(3000,20)],(2014,16.3),(2015,16.3),(2020,16.6),(2025,16.8),(2035,17.3),(2050,\
                18))
        ~       TWh/year
        ~               |

Pumping installed capacity=
        IF THEN ELSE( VSE SCENARIO = 1, Pump VSE1(Year),
        IF THEN ELSE( VSE SCENARIO = 2, Pump VSE2(Year),
        IF THEN ELSE( VSE SCENARIO = 3, Pump VSE3(Year),
        0)))
        ~       MW
        ~               |

Geo VSE1(
        [(0,0)-(3000,200)],(2014,0),(2015,0),(2035,0),(2050,200))
        ~       MW
        ~               |

Geo VSE2(
        [(0,0)-(3000,400)],(2014,0),(2025,0),(2035,100),(2050,400))
        ~       MW
        ~               |

Geo VSE3(
        [(0,0)-(3000,400)],(2014,0),(2025,0),(2035,100),(2050,400))
```

```
		~	MW
		~		|

Geothermal installed capacity=
		IF THEN ELSE( VSE SCENARIO = 1, Geo VSE1(Year),
		IF THEN ELSE( VSE SCENARIO = 2, Geo VSE2(Year),
		IF THEN ELSE( VSE SCENARIO = 3, Geo VSE3(Year),
		0)))
		~	MW
		~		|

Pump VSE1(
		[(2014,0)-(2050,4000)],(2014,1800),(2015,1800),(2020,4000),(2025,4000),(2035,4000),(\
			2050,4000))
		~	MW
		~		|

Pump VSE3(
		[(0,0)-(3000,4000)],(2014,1800),(2015,1800),(2020,4000),(2025,4000),(2035,4000),(2050\
			,4000))
		~	MW
		~		|

Pump VSE2(
		[(0,0)-(3000,4000)],(2014,1800),(2015,1800),(2020,4000),(2025,4000),(2035,4000),(2050\
			,4000))
		~	MW
		~		|

Demand VSE2(
		[(2014,0)-(2050,100)],(2014,67.16),(2015,67.16),(2020,69.41),(2025,71.04),(2035,72.82\
			),(2050,73.1))
		~	TWh/year
		~		|

Demand VSE3(
		[(0,0)-(3000,70)],(2015,66.99),(2020,68.67),(2025,69.4),(2035,68.2),(2050,60.5))
		~	TWh/year
		~		|

Demand VSE1(
		[(2014,6)-(2050,100)],(2014,67.08),(2015,67.08),(2020,69.69),(2025,72.08),(2035,76.22\
			),(2050,81))
		~	TWh/year
		~	\!\!
		|

Yearly inflow VSE3(
		[(0,0)-(3000,20)],(2014,18.8),(2015,18.8),(2020,18.9),(2025,19),(2035,19.3),(2050,19.6\
			))
		~	TWh/year
		~		|

Yearly inflow VSE2(
		[(0,0)-(3000,20)],(2014,18.8),(2015,18.8),(2020,18.8),(2035,18.9),(2050,19.1))
		~	TWh/year
		~		|

Yearly inflow VSE1(
		[(2014,15)-(2050,25)],(2014,18.6),(2015,18.6),(2020,18.6),(2025,18.5),(2035,18.3),(2050\
			,18.1))
		~	TWh/year
		~		|

NTC CH to DE AT(
		GET XLS LOOKUPS( 'Data.xlsx'  , 'Scenarios' , 'A' , 'G4' ))
		~	MW
		~		|

NTC CH to FR(
		GET XLS LOOKUPS( 'Data.xlsx'  , 'Scenarios' , 'A' , 'H4' ))
		~	MW
		~		|

NTC CH to IT(
		GET XLS LOOKUPS( 'Data.xlsx'  , 'Scenarios' , 'A' , 'I4' ))
		~	MW
		~		|

NTC DE AT to CH(
		GET XLS LOOKUPS( 'Data.xlsx'  , 'Scenarios' , 'A' , 'L4' ))
		~	MW
		~		|

NTC FR to CH(
		GET XLS LOOKUPS( 'Data.xlsx'  , 'Scenarios' , 'A' , 'M4' ))
		~	MW
		~		|

NTC IT to CH(
```

```
	GET XLS LOOKUPS( 'Data.xlsx'  , 'Scenarios' , 'A' , 'N4' ))
	~	MW
	~		|

ROR data 2010(
	GET XLS LOOKUPS( 'Data.xlsx' , '2010' , 'A' , 'N4' ))
	~	MW/((MW*Hour)/year)
	~		|

Inflow data 2010(
	GET XLS LOOKUPS( 'Data.xlsx' , '2010' , 'A' , 'M4' ))
	~	MW*Hour/Hour/(MW*Hour/year)
	~		|

FR available import NTC=
	FR hourly import NTC-FR import contracts amount
	~	MW
	~		|

VSE SCENARIO=
	1
	~	Dmnl
	~	From Pöyry 2012, 1 = increasing, 2 = stabile, 3 = decline (demand)
		Also does geothermal, pumping, hydro yearly inflow, ROR yearly production
	|

Wind investment subsidies=
	0
	~	Dmnl
	~		|

Wind subsidized capacity=
	Wind approved projects+Wind installed capacity+Wind under construction
	~	MW
	~		|

Wind operational subsidies=
	IF THEN ELSE(Wind subsidized capacity<Wind capacity target:AND:Year<=Year subsidy stop\
		,189,0)
	~	CHF/(MW*Hour)
	~		|

Solar operational costs=
	"Solar O&M"-Solar operational subsidies
	~	CHF/(MW*Hour)
	~		|

Solar operational subsidies=
	IF THEN ELSE(Solar subsidized capacity<Solar capacity target:AND:Year<=Subsidy year stop\
		,469,0)
	~	CHF/(MW*Hour)
	~	2032
	|

Wind operational costs=
	"Wind O&M"-Wind operational subsidies
	~	CHF/(MW*Hour)
	~		|

Wind capacity target = WITH LOOKUP (
	Year,
		([(2014,0)-(2050,1000)],(2014,60),(2015,60),(2020,279),(2035,919),(2036,0),(2050,0)\
		 ))
	~	MW
	~	Based off of Osorio (2016), with target of 4.4/14.5 TWh by renewables of \
		which 10% is wind @ an 18% availability factor
	|

Solar capacity target = WITH LOOKUP (
	Year,
		([(2014,0)-(2050,15000)],(2014,755),(2015,755),(2020,4110),(2035,13543),(2036,0),(2050\
		,0) ))
	~	MW
	~	From Osorio 2016, based off of 11% capacity factor and targets of 4.4/14.5 \
		TWh by 2020/2035, of which 90% is to be done by solar
	|

Interruptible contracts=
	0.05*Peak demand
	~	MW
	~		|

CCGT operational costs=
	Carbon price*Carbon content per MWh gas/CCGT firing efficiency+Fuel price+"CCGT O&M"
	~	CHF/(MW*Hour)
	~		|

Land scarcity = WITH LOOKUP (
	Available land,
		([(0,0)-(1,1)],(0,1),(0.138493,0.962085),(0.319756,0.914692),(0.439919,0.781991),(0.5\
```

```
                        ,0.5),(0.600815,0.165877),(0.729124,0.0663507),(1,0) ))
        ~               Dmnl
        ~                       |

Wind installed capacity increasing= INTEG (
        Wind completion rate,
                        100)
        ~               MW
        ~                       |

Fuel price=
        EUR to CHF*Fuel price EUR
        ~               CHF/(MW*Hour)
        ~                       |

Social response = WITH LOOKUP (
        Social acceptance,
                        ([(0,0)-(1,1)],(0,1),(0.209776,0.834123),(0.342159,0.682464),(0.5,0.436019),(0.625255\
                        ,0.21327),(0.743381,0.0616114),(1,0) ))
        ~               Dmnl
        ~                       |

Solar application rejection rate=
        0
        ~               MW/Hour
        ~                       |

Wind application delay=
        DELAY FIXED(Wind project application rate,Wind permitting time,Wind project application rate\
                        )
        ~               MW/Hour
        ~                       |

Spot price seasonal=
        IF THEN ELSE(Season=1,Winter spot price,
        IF THEN ELSE(Season=2,Spring spot price,
        IF THEN ELSE(Season=3,Summer spot price,
        IF THEN ELSE(Season=4,Fall spot price,Fall spot price))))
        ~               CHF/(MW*Hour)
        ~               Delayed by 1 year; i.e. this gives the summer value of 2013 in 2014
        |

Spring spot price=
        SAMPLE IF TRUE(Season=2:AND:Season end=1,Spot price seasonal sampling,50)
        ~               CHF/(MW*Hour)
        ~                       |

Solar investment costs=
        Solar initial investment costs*Solar learning curve*(1-Solar investment subsidies)
        ~               CHF/MW
        ~                       |

Summer spot price=
        SAMPLE IF TRUE(Season=3:AND:Season end=1,Spot price seasonal sampling,35)
        ~               CHF/(MW*Hour)
        ~                       |

CCGT annual fixed costs=
        42*1000
        ~               CHF/MW
        ~               From Poyry (2012), 42 CHF/kW/y
        |

CCGT investment costs=
        1015*1000
        ~               CHF/MW
        ~               From Poyry 2012, 1015 CHF/kW
        |

EUR to CHF=
        1.09
        ~               CHF/EUR
        ~               Google, April 7th 2016 (highly rounded)
        |

Solar annual fixed costs CHF = WITH LOOKUP (
        Year,
                        ([(2014,0)-(2050,40000)],(2014,33000),(2015,33000),(2020,26000),(2025,23000),(2035,\
                        20000),(2050,15000) ))
        ~               CHF/MW
        ~               Poyry (2012)
        |

Wind decomissioning rate=
        Wind installed capacity/(Wind lifetime)
        ~               MW/Hour
        ~                       |

Winter spot price=
        SAMPLE IF TRUE(Season=1:AND:Season end=1,Spot price seasonal sampling,75)
```

```
		~	CHF/(MW*Hour)
		~		|

Fall spot price=
		SAMPLE IF TRUE(Season=4:AND:Season end=1,Spot price seasonal sampling,45)
		~	CHF/(MW*Hour)
		~		|

CCGT CR J=
		IF THEN ELSE(CCGT installed capacity 8>0:AND:CCGT installed capacity J=0:AND:CCGT completion rate cumulative\
			>0,CCGT completion rate cumulative,0)
		~	MW/Hour
		~		|

CCGT CR K=
		IF THEN ELSE(CCGT installed capacity I>0:AND:CCGT installed capacity K=0:AND:CCGT completion rate cumulative\
			>0,CCGT completion rate cumulative,0)
		~	MW/Hour
		~		|

CCGT CR L=
		IF THEN ELSE(CCGT installed capacity J>0:AND:CCGT installed capacity L=0:AND:CCGT completion rate cumulative\
			>0,CCGT completion rate cumulative,0)
		~	MW/Hour
		~		|

CCGT CR M=
		IF THEN ELSE(CCGT installed capacity K>0:AND:CCGT installed capacity M=0:AND:CCGT completion rate cumulative\
			>0,CCGT completion rate cumulative,0)
		~	MW/Hour
		~		|

CCGT CR N=
		IF THEN ELSE(CCGT installed capacity L>0:AND:CCGT installed capacity N=0:AND:CCGT completion rate cumulative\
			>0,CCGT completion rate cumulative,0)
		~	MW/Hour
		~		|

CCGT CR O=
		IF THEN ELSE(CCGT installed capacity M>0:AND:CCGT installed capacity O=0:AND:CCGT completion rate cumulative\
			>0,CCGT completion rate cumulative,0)
		~	MW/Hour
		~		|

CCGT CR P=
		IF THEN ELSE(CCGT installed capacity N>0:AND:CCGT installed capacity P=0:AND:CCGT completion rate cumulative\
			>0,CCGT completion rate cumulative,0)
		~	MW/Hour
		~		|

CCGT CR Q=
		IF THEN ELSE(CCGT installed capacity O>0:AND:CCGT installed capacity Q=0:AND:CCGT completion rate cumulative\
			>0,CCGT completion rate cumulative,0)
		~	MW/Hour
		~		|

CCGT installed capacity in forecast module=
		CCGT installed capacity 0+CCGT installed capacity 1+CCGT installed capacity 2+CCGT installed capacity 3\
			+CCGT installed capacity 4
		+CCGT installed capacity 5+CCGT installed capacity 6+CCGT installed capacity 7+CCGT installed capacity 8\
			+CCGT installed capacity 9
		+CCGT installed capacity 27+CCGT installed capacity A+CCGT installed capacity B+CCGT installed capacity C\
			+CCGT installed capacity D
		+CCGT installed capacity E+CCGT installed capacity F+CCGT installed capacity G+CCGT installed capacity H\
			+CCGT installed capacity I
		+CCGT installed capacity J+CCGT installed capacity K+CCGT installed capacity L+CCGT installed capacity M\
			+CCGT installed capacity N
		+CCGT installed capacity O+CCGT installed capacity P+CCGT installed capacity Q
		~	MW
		~		|

CCGT CR S=
		IF THEN ELSE(CCGT installed capacity R>0:AND:CCGT deconstruction rate forecast>0:AND:\
			CCGT installed capacity S=0,CCGT deconstruction rate forecast,0)
		~	MW/Hour
		~		|

CCGT installed capacity 9= INTEG (
		CCGT CR 9-CCGT deconstruction rate 9,
			0)
		~	MW
		~		|

CCGT CR U=
		IF THEN ELSE(CCGT installed capacity T>0:AND:CCGT deconstruction rate forecast>0:AND:\
			CCGT installed capacity U=0,CCGT deconstruction rate forecast,0)
		~	MW/Hour
		~		|

Sample size CR 9=
```

```
        SAMPLE IF TRUE(CCGT CR 9>0,CCGT CR 9,0)
        ~       MW/Hour
        ~               |

CCGT decomissioning rate=
        CCGT deconstruction rate cumulative
        ~       MW/Hour
        ~               |

CCGT installed capacity cumulative=
        CCGT installed capacity in forecast module+CCGT installed capacity R+CCGT installed capacity S\
                +CCGT installed capacity T+CCGT installed capacity U
        ~       MW
        ~               |

CCGT CR 4=
        IF THEN ELSE(CCGT installed capacity 3>0:AND:CCGT installed capacity 4=0:AND:CCGT completion rate cumulative\
                >0,CCGT completion rate cumulative,0)
        ~       MW/Hour
        ~               |

CCGT CR 5=
        IF THEN ELSE(CCGT installed capacity 4>0:AND:CCGT installed capacity 5=0:AND:CCGT completion rate cumulative\
                >0,CCGT completion rate cumulative,0)
        ~       MW/Hour
        ~               |

CCGT CR 6=
        IF THEN ELSE(CCGT installed capacity 5>0:AND:CCGT installed capacity 6=0:AND:CCGT completion rate cumulative\
                >0,CCGT completion rate cumulative,0)
        ~       MW/Hour
        ~               |

CCGT installed capacity forecast=
        CCGT installed capacity in forecast module+CCGT under construction+75
        ~       MW
        ~       75 from already installed capacity
        |

Sample time CR T=
        SAMPLE IF TRUE(CCGT CR T>0,Time,0)
        ~       Hour
        ~               |

Sample time CR U=
        SAMPLE IF TRUE(CCGT CR U>0,Time,0)
        ~       Hour
        ~               |

CCGT CR A=
        IF THEN ELSE(CCGT installed capacity 9>0:AND:CCGT installed capacity A=0:AND:CCGT completion rate cumulative\
                >0,CCGT completion rate cumulative,0)
        ~       MW/Hour
        ~               |

Sample time CR S=
        SAMPLE IF TRUE(CCGT CR S>0,Time,0)
        ~       Hour
        ~               |

CCGT CR C=
        IF THEN ELSE(CCGT installed capacity B>0:AND:CCGT installed capacity C=0:AND:CCGT completion rate cumulative\
                >0,CCGT completion rate cumulative,0)
        ~       MW/Hour
        ~               |

CCGT CR D=
        IF THEN ELSE(CCGT installed capacity C>0:AND:CCGT installed capacity D=0:AND:CCGT completion rate cumulative\
                >0,CCGT completion rate cumulative,0)
        ~       MW/Hour
        ~               |

CCGT CR E=
        IF THEN ELSE(CCGT installed capacity D>0:AND:CCGT installed capacity E=0:AND:CCGT completion rate cumulative\
                >0,CCGT completion rate cumulative,0)
        ~       MW/Hour
        ~               |

CCGT CR F=
        IF THEN ELSE(CCGT installed capacity E>0:AND:CCGT installed capacity F=0:AND:CCGT completion rate cumulative\
                >0,CCGT completion rate cumulative,0)
        ~       MW/Hour
        ~               |

CCGT CR G=
        IF THEN ELSE(CCGT installed capacity F>0:AND:CCGT installed capacity G=0:AND:CCGT completion rate cumulative\
                >0,CCGT completion rate cumulative,0)
        ~       MW/Hour
        ~               |
```

```
CCGT deconstruction rate cumulative=
        CCGT deconstruction rate R+CCGT deconstruction rate S+CCGT deconstruction rate T+CCGT deconstruction rate U
        ~       MW/Hour
        ~               |

CCGT CR I=
        IF THEN ELSE(CCGT installed capacity H>0:AND:CCGT installed capacity I=0:AND:CCGT completion rate cumulative\
                >0,CCGT completion rate cumulative,0)
        ~       MW/Hour
        ~               |

Sample time CR 9=
        SAMPLE IF TRUE(CCGT CR 9>0,Time,0)
        ~       Hour
        ~               |

Sample size CR S=
        SAMPLE IF TRUE(CCGT CR S>0,CCGT CR S,0)
        ~       MW/Hour
        ~               |

CCGT installed capacity S= INTEG (
        CCGT CR S-CCGT deconstruction rate S,
                0)
        ~       MW
        ~               |

CCGT installed capacity T= INTEG (
        CCGT CR T-CCGT deconstruction rate T,
                0)
        ~       MW
        ~               |

CCGT installed capacity U= INTEG (
        CCGT CR U-CCGT deconstruction rate U,
                0)
        ~       MW
        ~               |

CCGT CR 9=
        IF THEN ELSE(CCGT installed capacity P>0:AND:CCGT installed capacity 9=0:AND:CCGT completion rate cumulative\
                >0,CCGT completion rate cumulative,0)
        ~       MW/Hour
        ~               |

CCGT CR 3=
        IF THEN ELSE(CCGT installed capacity 2>0:AND:CCGT installed capacity 3=0:AND:CCGT completion rate cumulative\
                >0,CCGT completion rate cumulative,0)
        ~       MW/Hour
        ~               |

CCGT CR B=
        IF THEN ELSE(CCGT installed capacity A>0:AND:CCGT installed capacity B=0:AND:CCGT completion rate cumulative\
                >0,CCGT completion rate cumulative,0)
        ~       MW/Hour
        ~               |

CCGT CR 2=
        IF THEN ELSE(CCGT installed capacity 1>0:AND:CCGT installed capacity 2=0:AND:CCGT completion rate cumulative\
                >0,CCGT completion rate cumulative,0)
        ~       MW/Hour
        ~               |

CCGT CR 0=
        IF THEN ELSE(CCGT installed capacity 27>0:AND:CCGT installed capacity 0=0:AND:CCGT completion rate cumulative\
                >0,CCGT completion rate cumulative,0)
        ~       MW/Hour
        ~               |

CCGT CR 1=
        IF THEN ELSE(CCGT installed capacity 0>0:AND:CCGT installed capacity 1=0:AND:CCGT completion rate cumulative\
                >0,CCGT completion rate cumulative,0)
        ~       MW/Hour
        ~               |

CCGT CR 7=
        IF THEN ELSE(CCGT installed capacity 6>0:AND:CCGT installed capacity 7=0:AND:CCGT completion rate cumulative\
                >0,CCGT completion rate cumulative,0)
        ~       MW/Hour
        ~               |

Sample size CR U=
        SAMPLE IF TRUE(CCGT CR U>0,CCGT CR U,0)
        ~       MW/Hour
        ~               |

CCGT CR H=
        IF THEN ELSE(CCGT installed capacity G>0:AND:CCGT installed capacity H=0:AND:CCGT completion rate cumulative\
                >0,CCGT completion rate cumulative,0)
        ~       MW/Hour
```

```
        ~               |

Sample size CR T=
        SAMPLE IF TRUE(CCGT CR T>0,CCGT CR T,0)
        ~       MW/Hour
        ~               |

CCGT CR 8=
        IF THEN ELSE(CCGT installed capacity 7>0:AND:CCGT installed capacity 8=0:AND:CCGT completion rate cumulative\
                >0,CCGT completion rate cumulative,0)
        ~       MW/Hour
        ~               |

CCGT deconstruction rate S=
        IF THEN ELSE(Time=Sample time CR S+CCGT forecast time,Sample size CR S,0)
        ~       MW/Hour
        ~               |

CCGT deconstruction rate T=
        IF THEN ELSE(Time=Sample time CR T+CCGT forecast time,Sample size CR T,0)
        ~       MW/Hour
        ~               |

CCGT deconstruction rate U=
        IF THEN ELSE(Time=Sample time CR U+CCGT forecast time,Sample size CR U,0)
        ~       MW/Hour
        ~               |

CCGT CR T=
        IF THEN ELSE(CCGT installed capacity S>0:AND:CCGT deconstruction rate forecast>0:AND:\
                CCGT installed capacity T=0,CCGT deconstruction rate forecast,0)
        ~       MW/Hour
        ~               |

Sample time CR C=
        SAMPLE IF TRUE(CCGT CR C>0,Time,0)
        ~       Hour
        ~               |

Sample time CR D=
        SAMPLE IF TRUE(CCGT CR D>0,Time,0)
        ~       Hour
        ~               |

Sample time CR E=
        SAMPLE IF TRUE(CCGT CR E>0,Time,0)
        ~       Hour
        ~               |

Sample time CR F=
        SAMPLE IF TRUE(CCGT CR F>0,Time,0)
        ~       Hour
        ~               |

Sample time CR G=
        SAMPLE IF TRUE(CCGT CR G>0,Time,0)
        ~       Hour
        ~               |

Sample time CR H=
        SAMPLE IF TRUE(CCGT CR H>0,Time,0)
        ~       Hour
        ~               |

CCGT installed capacity A= INTEG (
        CCGT CR A-CCGT deconstruction rate A,
                0)
        ~       MW
        ~               |

CCGT installed capacity B= INTEG (
        CCGT CR B-CCGT deconstruction rate B,
                0)
        ~       MW
        ~               |

CCGT installed capacity C= INTEG (
        CCGT CR C-CCGT deconstruction rate C,
                0)
        ~       MW
        ~               |

CCGT installed capacity D= INTEG (
        CCGT CR D-CCGT deconstruction rate D,
                0)
        ~       MW
        ~               |

CCGT installed capacity E= INTEG (
        CCGT CR E-CCGT deconstruction rate E,
```

```
			0)
	~		MW
	~				|

CCGT installed capacity F= INTEG (
	CCGT CR F-CCGT deconstruction rate F,
			0)
	~		MW
	~				|

Sample time CR P=
	SAMPLE IF TRUE(CCGT CR P>0,Time,0)
	~		Hour
	~				|

CCGT installed capacity G= INTEG (
	CCGT CR G-CCGT deconstruction rate G,
			0)
	~		MW
	~				|

CCGT installed capacity H= INTEG (
	CCGT CR H-CCGT deconstruction rate H,
			0)
	~		MW
	~				|

CCGT installed capacity I= INTEG (
	CCGT CR I-CCGT deconstruction rate I,
			0)
	~		MW
	~				|

CCGT installed capacity J= INTEG (
	CCGT CR J-CCGT deconstruction rate J,
			0)
	~		MW
	~				|

CCGT installed capacity K= INTEG (
	CCGT CR K-CCGT deconstruction rate K,
			0)
	~		MW
	~				|

CCGT installed capacity L= INTEG (
	CCGT CR L-CCGT deconstruction rate L,
			0)
	~		MW
	~				|

CCGT installed capacity M= INTEG (
	CCGT CR M-CCGT deconstruction rate M,
			0)
	~		MW
	~				|

CCGT installed capacity N= INTEG (
	CCGT CR N-CCGT deconstruction rate N,
			0)
	~		MW
	~				|

CCGT installed capacity O= INTEG (
	CCGT CR O-CCGT deconstruction rate O,
			0)
	~		MW
	~				|

CCGT installed capacity P= INTEG (
	CCGT CR P-CCGT deconstruction rate P,
			0)
	~		MW
	~				|

CCGT installed capacity Q= INTEG (
	CCGT CR Q-CCGT deconstruction rate Q,
			0)
	~		MW
	~				|

CCGT installed capacity R= INTEG (
	CCGT CR R-CCGT deconstruction rate R,
			0)
	~		MW
	~				|

CCGT deconstruction rate C=
	IF THEN ELSE(Time=Sample time CR C+CCGT lifetime forecast,Sample size CR C,0)
	~		MW/Hour
```

```
	~		|

CCGT deconstruction rate D=
	IF THEN ELSE(Time=Sample time CR D+CCGT lifetime forecast,Sample size CR D,0)
	~	MW/Hour
	~		|

CCGT deconstruction rate E=
	IF THEN ELSE(Time=Sample time CR E+CCGT lifetime forecast,Sample size CR E,0)
	~	MW/Hour
	~		|

CCGT deconstruction rate F=
	IF THEN ELSE(Time=Sample time CR F+CCGT lifetime forecast,Sample size CR F,0)
	~	MW/Hour
	~		|

CCGT deconstruction rate forecast=
	CCGT deconstruction rate 0+CCGT deconstruction rate 1+CCGT deconstruction rate 2+CCGT deconstruction rate 3\
		+CCGT deconstruction rate 4+CCGT deconstruction rate 5+CCGT deconstruction rate 6+CCGT deconstruction rate 7\
		+CCGT deconstruction rate 8+CCGT deconstruction rate 9+CCGT deconstruction rate A+CCGT deconstruction rate B\
		+CCGT deconstruction rate C+CCGT deconstruction rate D+CCGT deconstruction rate E+CCGT deconstruction rate F\
		+CCGT deconstruction rate G+CCGT deconstruction rate H+CCGT deconstruction rate I+CCGT deconstruction rate J\
		+CCGT deconstruction rate K+CCGT deconstruction rate L+CCGT deconstruction rate M+CCGT deconstruction rate N\
		+CCGT deconstruction rate O+CCGT deconstruction rate P+CCGT deconstruction rate Q+CCGT deconstruction rate 27
	~	MW/Hour
	~		|

CCGT deconstruction rate G=
	IF THEN ELSE(Time=Sample time CR G+CCGT lifetime forecast,Sample size CR G,0)
	~	MW/Hour
	~		|

CCGT deconstruction rate H=
	IF THEN ELSE(Time=Sample time CR H+CCGT lifetime forecast,Sample size CR H,0)
	~	MW/Hour
	~		|

CCGT deconstruction rate I=
	IF THEN ELSE(Time=Sample time CR I+CCGT lifetime forecast,Sample size CR I,0)
	~	MW/Hour
	~		|

CCGT deconstruction rate J=
	IF THEN ELSE(Time=Sample time CR J+CCGT lifetime forecast,Sample size CR J,0)
	~	MW/Hour
	~		|

CCGT deconstruction rate K=
	IF THEN ELSE(Time=Sample time CR K+CCGT lifetime forecast,Sample size CR K,0)
	~	MW/Hour
	~		|

CCGT deconstruction rate L=
	IF THEN ELSE(Time=Sample time CR L+CCGT lifetime forecast,Sample size CR L,0)
	~	MW/Hour
	~		|

CCGT deconstruction rate M=
	IF THEN ELSE(Time=Sample time CR M+CCGT lifetime forecast,Sample size CR M,0)
	~	MW/Hour
	~		|

CCGT deconstruction rate N=
	IF THEN ELSE(Time=Sample time CR N+CCGT lifetime forecast,Sample size CR N,0)
	~	MW/Hour
	~		|

CCGT deconstruction rate R=
	IF THEN ELSE(Time=Sample time CR R+CCGT forecast time,Sample size CR R,0)
	~	MW/Hour
	~		|

CCGT CR R=
	IF THEN ELSE(CCGT deconstruction rate forecast>0:AND:CCGT installed capacity R=0,CCGT deconstruction rate forecast\
		,0)
	~	MW/Hour
	~		|

Sample size CR A=
	SAMPLE IF TRUE(CCGT CR A>0,CCGT CR A,0)
	~	MW/Hour
	~		|

Sample size CR B=
	SAMPLE IF TRUE(CCGT CR B>0,CCGT CR B,0)
	~	MW/Hour
	~		|

Sample size CR C=
```

```
            SAMPLE IF TRUE(CCGT CR C>0,CCGT CR C,0)
            ~           MW/Hour
            ~                       |

Sample size CR D=
            SAMPLE IF TRUE(CCGT CR D>0,CCGT CR D,0)
            ~           MW/Hour
            ~                       |

Sample size CR E=
            SAMPLE IF TRUE(CCGT CR E>0,CCGT CR E,0)
            ~           MW/Hour
            ~                       |

Sample size CR F=
            SAMPLE IF TRUE(CCGT CR F>0,CCGT CR F,0)
            ~           MW/Hour
            ~                       |

Sample size CR G=
            SAMPLE IF TRUE(CCGT CR G>0,CCGT CR G,0)
            ~           MW/Hour
            ~                       |

Sample size CR H=
            SAMPLE IF TRUE(CCGT CR H>0,CCGT CR H,0)
            ~           MW/Hour
            ~                       |

Sample size CR I=
            SAMPLE IF TRUE(CCGT CR I>0,CCGT CR I,0)
            ~           MW/Hour
            ~                       |

Sample size CR J=
            SAMPLE IF TRUE(CCGT CR J>0,CCGT CR J,0)
            ~           MW/Hour
            ~                       |

Sample size CR K=
            SAMPLE IF TRUE(CCGT CR K>0,CCGT CR K,0)
            ~           MW/Hour
            ~                       |

CCGT deconstruction rate 9=
            IF THEN ELSE(Time=Sample time CR 9+CCGT lifetime forecast,Sample size CR 9,0)
            ~           MW/Hour
            ~                       |

CCGT deconstruction rate A=
            IF THEN ELSE(Time=Sample time CR A+CCGT lifetime forecast,Sample size CR A,0)
            ~           MW/Hour
            ~                       |

CCGT deconstruction rate B=
            IF THEN ELSE(Time=Sample time CR B+CCGT lifetime forecast,Sample size CR B,0)
            ~           MW/Hour
            ~                       |

Sample size CR O=
            SAMPLE IF TRUE(CCGT CR O>0,CCGT CR O,0)
            ~           MW/Hour
            ~                       |

Sample size CR P=
            SAMPLE IF TRUE(CCGT CR P>0,CCGT CR P,0)
            ~           MW/Hour
            ~                       |

Sample size CR Q=
            SAMPLE IF TRUE(CCGT CR Q>0,CCGT CR Q,0)
            ~           MW/Hour
            ~                       |

Sample size CR R=
            SAMPLE IF TRUE(CCGT CR R>0,CCGT CR R,0)
            ~           MW/Hour
            ~                       |

Sample time CR R=
            SAMPLE IF TRUE(CCGT CR R>0,Time,0)
            ~           Hour
            ~                       |

Sample time CR L=
            SAMPLE IF TRUE(CCGT CR L>0,Time,0)
            ~           Hour
            ~                       |

CCGT deconstruction rate O=
```

```
	IF THEN ELSE(Time=Sample time CR O+CCGT lifetime forecast,Sample size CR O,0)
	~	MW/Hour
	~		|

CCGT deconstruction rate P=
	IF THEN ELSE(Time=Sample time CR P+CCGT lifetime forecast,Sample size CR P,0)
	~	MW/Hour
	~		|

CCGT deconstruction rate Q=
	IF THEN ELSE(Time=Sample time CR Q+CCGT lifetime forecast,Sample size CR Q,0)
	~	MW/Hour
	~		|

Sample time CR I=
	SAMPLE IF TRUE(CCGT CR I>0,Time,0)
	~	Hour
	~		|

Sample time CR J=
	SAMPLE IF TRUE(CCGT CR J>0,Time,0)
	~	Hour
	~		|

Sample time CR K=
	SAMPLE IF TRUE(CCGT CR K>0,Time,0)
	~	Hour
	~		|

Sample size CR L=
	SAMPLE IF TRUE(CCGT CR L>0,CCGT CR L,0)
	~	MW/Hour
	~		|

Sample size CR M=
	SAMPLE IF TRUE(CCGT CR M>0,CCGT CR M,0)
	~	MW/Hour
	~		|

Sample time CR A=
	SAMPLE IF TRUE(CCGT CR A>0,Time,0)
	~	Hour
	~		|

Sample time CR B=
	SAMPLE IF TRUE(CCGT CR B>0,Time,0)
	~	Hour
	~		|

Sample time CR Q=
	SAMPLE IF TRUE(CCGT CR Q>0,Time,0)
	~	Hour
	~		|

Sample time CR N=
	SAMPLE IF TRUE(CCGT CR N>0,Time,0)
	~	Hour
	~		|

Sample time CR O=
	SAMPLE IF TRUE(CCGT CR O>0,Time,0)
	~	Hour
	~		|

Sample time CR M=
	SAMPLE IF TRUE(CCGT CR M>0,Time,0)
	~	Hour
	~		|

Sample size CR N=
	SAMPLE IF TRUE(CCGT CR N>0,CCGT CR N,0)
	~	MW/Hour
	~		|

CCGT deconstruction rate 4=
	IF THEN ELSE(Time=Sample time CR 4+CCGT lifetime forecast,Sample size CR 4,0)
	~	MW/Hour
	~		|

CCGT deconstruction rate 5=
	IF THEN ELSE(Time=Sample time CR 5+CCGT lifetime forecast,Sample size CR 5,0)
	~	MW/Hour
	~		|

CCGT deconstruction rate 6=
	IF THEN ELSE(Time=Sample time CR 6+CCGT lifetime forecast,Sample size CR 6,0)
	~	MW/Hour
	~		|

CCGT deconstruction rate 7=
```

```
		IF THEN ELSE(Time=Sample time CR 7+CCGT lifetime forecast,Sample size CR 7,0)
		~		MW/Hour
		~				|

CCGT deconstruction rate 8=
		IF THEN ELSE(Time=Sample time CR 8+CCGT lifetime forecast,Sample size CR 8,0)
		~		MW/Hour
		~				|

CCGT deconstruction rate 3=
		IF THEN ELSE(Time=Sample time CR 3+CCGT lifetime forecast,Sample size CR 3,0)
		~		MW/Hour
		~				|

CCGT deconstruction rate 27=
		IF THEN ELSE(Time=Sample time CR 27+CCGT lifetime forecast,Sample size CR 27,0)
		~		MW/Hour
		~				|

CCGT deconstruction rate 0=
		IF THEN ELSE(Time=Sample time CR 0+CCGT lifetime forecast,Sample size CR 0,0)
		~		MW/Hour
		~				|

CCGT deconstruction rate 1=
		IF THEN ELSE(Time=Sample time CR 1+CCGT lifetime forecast,Sample size CR 1,0)
		~		MW/Hour
		~				|

CCGT deconstruction rate 2=
		IF THEN ELSE(Time=Sample time CR 2+CCGT lifetime forecast,Sample size CR 2,0)
		~		MW/Hour
		~				|

CCGT CR 27=
		IF THEN ELSE(CCGT installed capacity 27=0:AND:CCGT completion rate cumulative>0,CCGT completion rate cumulative\
			,0)
		~		MW/Hour
		~				|

Sample size CR 0=
		SAMPLE IF TRUE(CCGT CR 0>0,CCGT CR 0,0)
		~		MW/Hour
		~				|

Sample size CR 1=
		SAMPLE IF TRUE(CCGT CR 1>0,CCGT CR 1,0)
		~		MW/Hour
		~				|

CCGT installed capacity 0= INTEG (
		CCGT CR 0-CCGT deconstruction rate 0,
			0)
		~		MW
		~				|

CCGT forecast time=
		3*8760
		~		Hour
		~				|

CCGT installed capacity 7= INTEG (
		CCGT CR 7-CCGT deconstruction rate 7,
			0)
		~		MW
		~				|

CCGT installed capacity 8= INTEG (
		CCGT CR 8-CCGT deconstruction rate 8,
			0)
		~		MW
		~				|

Sample time CR 8=
		SAMPLE IF TRUE(CCGT CR 8>0,Time,0)
		~		Hour
		~				|

CCGT installed capacity 27= INTEG (
		CCGT CR 27-CCGT deconstruction rate 27,
			0)
		~		MW
		~				|

CCGT installed capacity 5= INTEG (
		CCGT CR 5-CCGT deconstruction rate 5,
			0)
		~		MW
		~				|
```

```
CCGT installed capacity 1= INTEG (
        CCGT CR 1-CCGT deconstruction rate 1,
                0)
        ~       MW
        ~               |

CCGT installed capacity 2= INTEG (
        CCGT CR 2-CCGT deconstruction rate 2,
                0)
        ~       MW
        ~               |

CCGT installed capacity 3= INTEG (
        CCGT CR 3-CCGT deconstruction rate 3,
                0)
        ~       MW
        ~               |

CCGT installed capacity 4= INTEG (
        CCGT CR 4-CCGT deconstruction rate 4,
                0)
        ~       MW
        ~               |

Sample size CR 27=
        SAMPLE IF TRUE(CCGT CR 27>0,CCGT CR 27,0)
        ~       MW/Hour
        ~               |

CCGT installed capacity 6= INTEG (
        CCGT CR 6-CCGT deconstruction rate 6,
                0)
        ~       MW
        ~               |

Sample size CR 7=
        SAMPLE IF TRUE(CCGT CR 7>0,CCGT CR 7,0)
        ~       MW/Hour
        ~               |

Sample size CR 8=
        SAMPLE IF TRUE(CCGT CR 8>0,CCGT CR 8,0)
        ~       MW/Hour
        ~               |

Sample time CR 7=
        SAMPLE IF TRUE(CCGT CR 7>0,Time,0)
        ~       Hour
        ~               |

CCGT lifetime=
        25*8760
        ~       Hour
        ~               |

CCGT lifetime forecast=
        CCGT lifetime-CCGT forecast time
        ~       Hour
        ~               |

Sample size CR 2=
        SAMPLE IF TRUE(CCGT CR 2>0,CCGT CR 2,0)
        ~       MW/Hour
        ~               |

Sample size CR 3=
        SAMPLE IF TRUE(CCGT CR 3>0,CCGT CR 3,0)
        ~       MW/Hour
        ~               |

Sample time CR 1=
        SAMPLE IF TRUE(CCGT CR 1>0,Time,0)
        ~       Hour
        ~               |

Sample size CR 4=
        SAMPLE IF TRUE(CCGT CR 4>0,CCGT CR 4,0)
        ~       MW/Hour
        ~               |

Sample size CR 6=
        SAMPLE IF TRUE(CCGT CR 6>0,CCGT CR 6,0)
        ~       MW/Hour
        ~               |

Sample time CR 5=
        SAMPLE IF TRUE(CCGT CR 5>0,Time,0)
        ~       Hour
        ~               |
```

```
Sample time CR 6=
	SAMPLE IF TRUE(CCGT CR 6>0,Time,0)
	~	Hour
	~		|

Sample size CR 5=
	SAMPLE IF TRUE(CCGT CR 5>0,CCGT CR 5,0)
	~	MW/Hour
	~		|

Sample time CR 27=
	SAMPLE IF TRUE(CCGT CR 27>0,Time,0)
	~	Hour
	~		|

Sample time CR 0=
	SAMPLE IF TRUE(CCGT CR 0>0,Time,0)
	~	Hour
	~		|

Sample time CR 2=
	SAMPLE IF TRUE(CCGT CR 2>0,Time,0)
	~	Hour
	~		|

Sample time CR 4=
	SAMPLE IF TRUE(CCGT CR 4>0,Time,0)
	~	Hour
	~		|

Sample time CR 3=
	SAMPLE IF TRUE(CCGT CR 3>0,Time,0)
	~	Hour
	~		|

CCGT application approval rate 2=
	IF THEN ELSE(Time=Sample time CP 2+CCGT permitting time,Sample size CP 2,0)
	~	MW/Hour
	~		|

CCGT application approval rate 3=
	IF THEN ELSE(Time=Sample time CP 3+CCGT permitting time,Sample size CP 3,0)
	~	MW/Hour
	~		|

CCGT in permitting process cumulative=
	CCGT in permitting process 0+CCGT in permitting process 1+CCGT in permitting process 2\
		+CCGT in permitting process 3+CCGT in permitting process 4
	~	MW
	~		|

CCGT application rate cumulative=
	CCGT project application rate 0+CCGT project application rate 1+CCGT project application rate 2\
		+CCGT project application rate 3+CCGT project application rate 4
	~	MW/Hour
	~		|

CCGT application approval cumulative=
	CCGT application approval rate 0+CCGT application approval rate 1+CCGT application approval rate 2\
		+CCGT application approval rate 3+CCGT application approval rate 4
	~	MW/Hour
	~		|

CCGT application approval rate=
	CCGT application approval cumulative
	~	MW/Hour
	~		|

CCGT application approval rate 4=
	IF THEN ELSE(Time=Sample time CP 4+CCGT permitting time,Sample size CP 4,0)
	~	MW/Hour
	~		|

CCGT application approval rate 1=
	IF THEN ELSE(Time=Sample time CP 1+CCGT permitting time,Sample size CP 1,0)
	~	MW/Hour
	~		|

CCGT project application rate=
	CCGT application rate cumulative
	~	MW/Hour
	~		|

CCGT project application rate 3=
	IF THEN ELSE(CCGT in permitting process 2>0:AND:CCGT in permitting process 3=0:AND:CCGT application decision\
		>0,CCGT application decision,0)
	~	MW/Hour
	~		|

CCGT project application rate 4=
```

```
	IF THEN ELSE(CCGT in permitting process 3>0:AND:CCGT in permitting process 4=0:AND:CCGT application decision\
		>0,CCGT application decision,0)
	~	MW/Hour
	~		|

CCGT project application rate 2=
	IF THEN ELSE(CCGT in permitting process 1>0:AND:CCGT in permitting process 2=0:AND:CCGT application decision\
		>0,CCGT application decision,0)
	~	MW/Hour
	~		|

CCGT project application rate 1=
	IF THEN ELSE(CCGT in permitting process 0>0:AND:CCGT in permitting process 1=0:AND:CCGT application decision\
		>0,CCGT application decision,0)
	~	MW/Hour
	~		|

CCGT project investment rate 0=
	IF THEN ELSE(CCGT under construction 0=0:AND:CCGT under construction 8>0:AND:CCGT investment decision\
		=1,CCGT average size,0)
	~	MW/Hour
	~		|

CCGT project investment rate 1=
	IF THEN ELSE(CCGT under construction 1=0:AND:CCGT under construction 0>0:AND:CCGT investment decision\
		=1,CCGT average size,0)
	~	MW/Hour
	~		|

CCGT project investment rate 2=
	IF THEN ELSE(CCGT under construction 2=0:AND:CCGT under construction 1>0:AND:CCGT investment decision\
		=1,CCGT average size,0)
	~	MW/Hour
	~		|

CCGT project investment rate 3=
	IF THEN ELSE(CCGT under construction 3=0:AND:CCGT under construction 2>0:AND:CCGT investment decision\
		=1,CCGT average size,0)
	~	MW/Hour
	~		|

CCGT project investment rate 4=
	IF THEN ELSE(CCGT under construction 4=0:AND:CCGT under construction 3>0:AND:CCGT investment decision\
		=1,CCGT average size,0)
	~	MW/Hour
	~		|

CCGT project investment rate 5=
	IF THEN ELSE(CCGT under construction 5=0:AND:CCGT under construction 4>0:AND:CCGT investment decision\
		=1,CCGT average size,0)
	~	MW/Hour
	~		|

CCGT project investment rate 6=
	IF THEN ELSE(CCGT under construction 6=0:AND:CCGT under construction 5>0:AND:CCGT investment decision\
		=1,CCGT average size,0)
	~	MW/Hour
	~		|

CCGT project investment rate 7=
	IF THEN ELSE(CCGT under construction 7=0:AND:CCGT under construction 6>0:AND:CCGT investment decision\
		=1,CCGT average size,0)
	~	MW/Hour
	~		|

Sample size IC 7=
	SAMPLE IF TRUE(CCGT project investment rate 7>0,CCGT project investment rate 7,0)
	~	MW/Hour
	~		|

CCGT project investment rate cumulative=
	CCGT project investment rate 0+CCGT project investment rate 1+CCGT project investment rate 2\
		+CCGT project investment rate 3+CCGT project investment rate 4+CCGT project investment rate 5\
		+CCGT project investment rate 6+CCGT project investment rate 7+CCGT project investment rate 8
	~	MW/Hour
	~		|

Sample size CP 0=
	SAMPLE IF TRUE(CCGT project application rate 0>0,CCGT project application rate 0,0)
	~	MW/Hour
	~		|

CCGT in permitting process 0= INTEG (
	+CCGT project application rate 0-CCGT application approval rate 0,
		0)
	~	MW
	~		|

CCGT in permitting process 1= INTEG (
	+CCGT project application rate 1-CCGT application approval rate 1,
```

```
			0)
		~		MW
		~		|

CCGT in permitting process 2= INTEG (
		+CCGT project application rate 2-CCGT application approval rate 2,
			0)
		~		MW
		~		|

CCGT in permitting process 3= INTEG (
		+CCGT project application rate 3-CCGT application approval rate 3,
			0)
		~		MW
		~		|

CCGT in permitting process 4= INTEG (
		+CCGT project application rate 4-CCGT application approval rate 4,
			0)
		~		MW
		~		|

CCGT application approval rate 0=
		IF THEN ELSE(Time=Sample time CP 0+CCGT permitting time,Sample size CP 0,0)
		~		MW/Hour
		~		|

Sample time IC 7=
		SAMPLE IF TRUE(CCGT project investment rate 7>0,Time,0)
		~		Hour
		~		|

CCGT under construction cumulative=
		CCGT under construction 8+CCGT under construction 0+CCGT under construction 1+CCGT under construction 2\
			+CCGT under construction 3
		+CCGT under construction 4+CCGT under construction 5+CCGT under construction 6+CCGT under construction 7
		~		MW
		~		|

Sample time CP 0=
		SAMPLE IF TRUE(CCGT project application rate 0>0,Time,0)
		~		Hour
		~		|

CCGT completion rate=
		CCGT completion rate cumulative
		~		MW/Hour
		~		|

CCGT completion rate 0=
		IF THEN ELSE(Time=Sample time IC 0+CCGT construction time,Sample size IC 0,0)
		~		MW/Hour
		~		|

CCGT completion rate 1=
		IF THEN ELSE(Time=Sample time IC 1+CCGT construction time,Sample size IC 1,0)
		~		MW/Hour
		~		|

CCGT completion rate 2=
		IF THEN ELSE(Time=Sample time IC 2+CCGT construction time,Sample size IC 2,0)
		~		MW/Hour
		~		|

CCGT completion rate 3=
		IF THEN ELSE(Time=Sample time IC 3+CCGT construction time,Sample size IC 3,0)
		~		MW/Hour
		~		|

CCGT completion rate 4=
		IF THEN ELSE(Time=Sample time IC 4+CCGT construction time,Sample size IC 4,0)
		~		MW/Hour
		~		|

CCGT completion rate 5=
		IF THEN ELSE(Time=Sample time IC 5+CCGT construction time,Sample size IC 5,0)
		~		MW/Hour
		~		|

CCGT completion rate 6=
		IF THEN ELSE(Time=Sample time IC 6+CCGT construction time,Sample size IC 6,0)
		~		MW/Hour
		~		|

CCGT completion rate 7=
		IF THEN ELSE(Time=Sample time IC 7+CCGT construction time,Sample size IC 7,0)
		~		MW/Hour
		~		|

CCGT completion rate cumulative=
```

```
	CCGT completion rate 0+CCGT completion rate 1+CCGT completion rate 2+CCGT completion rate 3\
		+CCGT completion rate 4+CCGT completion rate 5+CCGT completion rate 6+CCGT completion rate 7\
		+CCGT completion rate 8
	~	MW/Hour
	~		|

CCGT project investment rate=
	CCGT project investment rate cumulative
	~	MW/Hour
	~		|

CCGT under construction 5= INTEG (
	+CCGT project investment rate 5-CCGT completion rate 5,
		0)
	~	MW
	~		|

Sample size IC 4=
	SAMPLE IF TRUE(CCGT project investment rate 4>0,CCGT project investment rate 4,0)
	~	MW/Hour
	~		|

Sample time IC 6=
	SAMPLE IF TRUE(CCGT project investment rate 6>0,Time,0)
	~	Hour
	~		|

CCGT under construction 7= INTEG (
	+CCGT project investment rate 7-CCGT completion rate 7,
		0)
	~	MW
	~		|

Sample size CP 3=
	SAMPLE IF TRUE(CCGT project application rate 3>0,CCGT project application rate 3,0)
	~	MW/Hour
	~		|

Sample size CP 4=
	SAMPLE IF TRUE(CCGT project application rate 4>0,CCGT project application rate 4,0)
	~	MW/Hour
	~		|

Sample size IC 5=
	SAMPLE IF TRUE(CCGT project investment rate 5>0,CCGT project investment rate 5,0)
	~	MW/Hour
	~		|

Sample size IC 6=
	SAMPLE IF TRUE(CCGT project investment rate 6>0,CCGT project investment rate 6,0)
	~	MW/Hour
	~		|

Sample time CP 3=
	SAMPLE IF TRUE(CCGT project application rate 3>0,Time,0)
	~	Hour
	~		|

Sample time CP 4=
	SAMPLE IF TRUE(CCGT project application rate 4>0,Time,0)
	~	Hour
	~		|

Sample size CP 1=
	SAMPLE IF TRUE(CCGT project application rate 1>0,CCGT project application rate 1,0)
	~	MW/Hour
	~		|

Sample size CP 2=
	SAMPLE IF TRUE(CCGT project application rate 2>0,CCGT project application rate 2,0)
	~	MW/Hour
	~		|

Sample time CP 2=
	SAMPLE IF TRUE(CCGT project application rate 2>0,Time,0)
	~	Hour
	~		|

CCGT under construction 4= INTEG (
	+CCGT project investment rate 4-CCGT completion rate 4,
		0)
	~	MW
	~		|

Sample time IC 4=
	SAMPLE IF TRUE(CCGT project investment rate 4>0,Time,0)
	~	Hour
	~		|

CCGT under construction 6= INTEG (
```

```
	+CCGT project investment rate 6-CCGT completion rate 6,
		0)
	~	MW
	~		|

Sample time IC 5=
	SAMPLE IF TRUE(CCGT project investment rate 5>0,Time,0)
	~	Hour
	~		|

Sample time CP 1=
	SAMPLE IF TRUE(CCGT project application rate 1>0,Time,0)
	~	Hour
	~		|

CCGT project application rate 0=
	IF THEN ELSE(CCGT in permitting process 0=0:AND:CCGT application decision>0,CCGT application decision\
		,0)
	~	MW/Hour
	~		|

Sample time IC 8=
	SAMPLE IF TRUE(CCGT project investment rate 8>0,Time,0)
	~	Hour
	~		|

CCGT under construction 8= INTEG (
	+CCGT project investment rate 8-CCGT completion rate 8,
		0)
	~	MW
	~		|

CCGT under construction 0= INTEG (
	+CCGT project investment rate 0-CCGT completion rate 0,
		0)
	~	MW
	~		|

CCGT under construction 1= INTEG (
	+CCGT project investment rate 1-CCGT completion rate 1,
		0)
	~	MW
	~		|

CCGT under construction 2= INTEG (
	+CCGT project investment rate 2-CCGT completion rate 2,
		0)
	~	MW
	~		|

CCGT under construction 3= INTEG (
	+CCGT project investment rate 3-CCGT completion rate 3,
		0)
	~	MW
	~		|

Sample time IC 0=
	SAMPLE IF TRUE(CCGT project investment rate 0>0,Time,0)
	~	Hour
	~		|

Sample time IC 1=
	SAMPLE IF TRUE(CCGT project investment rate 1>0,Time,0)
	~	Hour
	~		|

Sample time IC 2=
	SAMPLE IF TRUE(CCGT project investment rate 2>0,Time,0)
	~	Hour
	~		|

Sample time IC 3=
	SAMPLE IF TRUE(CCGT project investment rate 3>0,Time,0)
	~	Hour
	~		|

CCGT completion rate 8=
	IF THEN ELSE(Time=Sample time IC 8+CCGT construction time,Sample size IC 8,0)
	~	MW/Hour
	~		|

Sample size IC 3=
	SAMPLE IF TRUE(CCGT project investment rate 3>0,CCGT project investment rate 3,0)
	~	MW/Hour
	~		|

CCGT project investment rate 8=
	IF THEN ELSE(CCGT under construction 8=0:AND:CCGT investment decision=1,CCGT average size\
		,0)
	~	MW/Hour
```

```
	~		|

Sample size IC 0=
	SAMPLE IF TRUE(CCGT project investment rate 0>0,CCGT project investment rate 0,0)
	~	MW/Hour
	~		|

Sample size IC 1=
	SAMPLE IF TRUE(CCGT project investment rate 1>0,CCGT project investment rate 1,0)
	~	MW/Hour
	~		|

Sample size IC 2=
	SAMPLE IF TRUE(CCGT project investment rate 2>0,CCGT project investment rate 2,0)
	~	MW/Hour
	~		|

Sample size IC 8=
	SAMPLE IF TRUE(CCGT project investment rate 8>0,CCGT project investment rate 8,0)
	~	MW/Hour
	~		|

Solar lifetime=
	20*8760
	~	Hour
	~	Poyry (2012)
	|

Season end=
	IF THEN ELSE((MODULO(Time,2190)/2190)=0:AND:Time>0,1,0)
	~	Dmnl
	~		|

Solar application approval rate=
	DELAY FIXED(Solar project application rate,Solar park permitting time,Solar project application rate\
		)
	~	MW/Hour
	~		|

Solar project application rate=
	IF THEN ELSE(Week end=1:AND:Solar IRR>Solar hurdle rate,Solar average size,0)
	~	MW/Hour
	~		|

Week end=
	IF THEN ELSE((MODULO(Time,168)/168)=0,1,0)
	~	Dmnl
	~		|

Solar average size=
	40
	~	MW/Hour
	~	Maximum weekly increase found in Poyry (2012 p.A9) is 16 MW, but since of \
		the high resolution (weekly) a higher number is allowed to allow for more \
		direct curve following
	|

CCGT application rejection rate=
	0
	~	MW/Hour
	~		|

CCGT investment decision=
	IF THEN ELSE(CCGT approved projects>0:AND:CCGT IRR>CCGT hurdle rate,1,0)
	~	Dmnl
	~		|

CCGT project abandonment rate=
	0
	~	MW/Hour
	~		|

Wind annual fixed costs = WITH LOOKUP (
	Year,
		([(2014,0)-(2050,50000)],(2014,42000),(2015,42000),(2020,40000),(2025,38000),(2035,\
		37000),(2050,35000) ))
	~	CHF/MW
	~	From Poyry, 2012, in CHF/kW.
	|

CCGT price=
	CCGT operational costs
	~	CHF/(MW*Hour)
	~		|

Residual demand forecast=
	MAX(0,((1+Transmission losses)*Demand forecast)-Total VRES production forecast-"Net import/export balance forecast"\
		+Hydropower pumping)
	~	MW
	~		|
```

```
Nuclear installed capacity forecast= INTEG (
        -Nuclear phaseout 3y ahead,
                3278)
        ~       MW
        ~               |

FR import contracts maximum forecast = WITH LOOKUP (
        Year,
                ([(2014,0)-(2050,4000)],(2014,2688),(2017,1920),(2022,1664),(2027,1407),(2032,640),\
                (2037,0),(2050,0) ))
        ~       MW [0,4000]
        ~               |

Carbon content per MWh gas=
        0.18
        ~       tCO2/(MW*Hour)
        ~       Source: Poyry (2012), part B6.
        |

Fuel price EUR = WITH LOOKUP (
        Year,
                ([(2014,0)-(2050,50)],(2014,23.1),(2015,23.1),(2020,24.6),(2025,24.7),(2035,32.8),(\
                2050,33.4) ))
        ~       EUR/(MW*Hour)
        ~       Original source Poyry (2012) in EUR/MWh
                Same for all VSE scenarios
        |

Carbon price = WITH LOOKUP (
        IF THEN ELSE(Carbon price switch=1,Year,0),
                ([(2014,0)-(2050,70)],(2014,21.108),(2020,30.193),(2025,39.89),(2035,65.182),(2050,\
                65.18) ))
        ~       CHF/tCO2 [20,70]
        ~       Original prices from Poyry (2012) in EUR/tCO2. Used conversion factor 1EUR=1.09CHF \
                (Google, 29th March 2016)
                Same for all VSE scenarios
        |

CCGT firing efficiency = WITH LOOKUP (
        Year,
                ([(2014,0)-(2050,1)],(2014,0.52),(2020,0.53),(2025,0.535),(2035,0.54),(2050,0.54) )\
                )
        ~       Dmnl [0,1]
        ~       Source: Poyry (2012) part B6
        |

CCGT permitting time=
        2*8760
        ~       Hour
        ~       Has to be in hours (model time units)
                Maximum: 4 years (or add new stocks)
        |

Carbon price switch=
        1
        ~       Dmnl
        ~               |

CCGT approved projects= INTEG (
        CCGT application approval rate-CCGT project investment rate-CCGT project abandonment rate\
                ,
                0)
        ~       MW
        ~               |

CCGT average size=
        400
        ~       MW/Hour
        ~               |

CCGT construction time=
        2*8760
        ~       Hour
        ~       From Poyry (2012)
                Has to be in hours (time unit of model)
                Maximum: 8 years (or make new stocks)
        |

CCGT in permitting process= INTEG (
        -CCGT application approval rate+CCGT project application rate-CCGT application rejection rate\
                ,
                0)
        ~       MW
        ~               |

CCGT installed capacity= INTEG (
        CCGT completion rate-CCGT decomissioning rate,
                75)
        ~       MW
```

```
        ~               |

CCGT under construction= INTEG (
        CCGT project investment rate-CCGT completion rate,
                0)
        ~       MW
        ~               |

Solar learning curve = WITH LOOKUP (
        Year,
                ([(2014,1)-(2050,0.454545)],(2014,1),(2020,0.787879),(2025,0.69697),(2035,0.606061)\
                ,(2050,0.454545) ))
        ~       Dmnl
        ~       Based on value in Poyry (2012)
        |

Solar initial investment costs=
        3300*1000
        ~       CHF/MW
        ~       Poyry (2012)
        |

Solar in permitting process= INTEG (
        -Solar application approval rate+Solar project application rate-Solar application rejection rate\
                ,
                0)
        ~       MW
        ~               |

Solar park permitting time=
        1/12*8760
        ~       Hour
        ~               |

Solar under construction= INTEG (
        Solar investment decision-Solar completion rate,
                0)
        ~       MW
        ~               |

Solar approved projects= INTEG (
        Solar application approval rate-Solar investment decision-Solar project abandoning rate\
                ,
                0)
        ~       MW
        ~               |

Solar construction time=
        1*8760
        ~       Hour
        ~       Poyry (2012)
        |

Solar completion rate=
        DELAY FIXED(Solar investment decision,Solar construction time,Solar investment decision\
                )
        ~       MW/Hour
        ~               |

"Solar O&M"=
        0
        ~       CHF/(MW*Hour)
        ~               |

Solar investment subsidies=
        0
        ~       Dmnl
        ~               |

Wind lifetime=
        20*8760
        ~       Hour
        ~               |

"Wind O&M"=
        0
        ~       CHF/(MW*Hour)
        ~       Poyry 2012
        |

Wind approved projects= INTEG (
        Wind application approval rate-Wind investment decision-Wind project abandoning rate\
                ,
                0)
        ~       MW
        ~               |

Wind average size=
        100
        ~       MW/Hour
```

```
        ~       Maximum yearly increase found in Poyry (2012 p. 23)
        |

Wind completion rate=
        DELAY FIXED(Wind investment decision,Wind construction time,Wind investment decision\
                )
        ~       MW/Hour
        ~               |

Wind construction time=
        2*8760
        ~       Hour
        ~       Poyry (2012)
        |

Wind in permitting process= INTEG (
        -Wind application approval rate+Wind project application rate-Wind application rejection rate\
                ,
                0)
        ~       MW
        ~               |

Wind initial investment costs = WITH LOOKUP (
        Year,
                ([(2014,0)-(2050,3e+06)],(2014,2.1e+06),(2015,2.1e+06),(2020,2e+06),(2025,1.9e+06),\
                (2035,1.86e+06),(2050,1.77e+06) ))
        ~       CHF/MW
        ~       2015: 2100, 2020: 2000, 2025: 1900, 2035: 1860, 2050: 1770
        |

Wind installed capacity= INTEG (
        Wind completion rate-Wind decomissioning rate,
                100)
        ~       MW
        ~               |

Proximity to community = WITH LOOKUP (
        Available land,
                ([(0,0)-(1,1)],(0,1),(0.274949,0.886256),(0.403259,0.744076),(0.5,0.5),(0.600815,0.227488\
                ),(0.690428,0.0758294),(1,0) ))
        ~       Dmnl
        ~               |

Wind under construction= INTEG (
        Wind investment decision-Wind completion rate,
                0)
        ~       MW
        ~               |

Interruptible contracts price=
        900
        ~       CHF/(MW*Hour)
        ~       900
        |

FR import contract price=
        35
        ~       CHF/(MW*Hour)
        ~               |

Transmission losses=
        0.07
        ~       Dmnl
        ~               |

Year end=
        IF THEN ELSE((MODULO(Time,8760)/8760)=0:AND:Time>0,1,0)
        ~       Dmnl
        ~               |

Year= INTEG (
        IF THEN ELSE((MODULO(Time,8760)/8760)=0:AND:Time>1,1,0),
                2015)
        ~       Hour
        ~               |

Season= INTEG (
        IF THEN ELSE((MODULO(Time,2190)/2190)=0,1,0)-
        IF THEN ELSE((MODULO(Time,8760)/8760)=0,4,0),
                4)
        ~       Hour
        ~               |

Hour=
        1+MODULO(Time,24)
        ~       Hour
        ~               |

RES CHP installed capacity=
        56
```

```
		~		MW
		~		|

Geothermal price=
		20
		~		CHF/(MW*Hour)
		~		|

Waste burning installed capacity=
		178
		~		MW
		~		|

Other thermal price=
		37.25
		~		CHF/(MW*Hour)
		~		|

Waste burning price=
		7.3
		~		CHF/(MW*Hour)
		~		|

Nuclear price=
		7
		~		CHF/(MW*Hour)
		~		From Poyry
		|

RES CHP price=
		42.2
		~		CHF/(MW*Hour)
		~		|

VOLL=
		3000
		~		CHF/(MW*Hour)
		~		Cap is set at 3000, but high VOLL estimates (appropriate for a country \
				expensive like Switzerland is at 10000)
		|

Total VRES production=
		ROR production+Solar production+Wind production
		~		MW
		~		|
```

C. Full timeline of events related to Swiss-EU energy relations.

The final version of the timeline that was shown during interviews for Chapter 3 (p. 53) is shown below. The timeline was continuously improved while the interviews took place, based on the information gathered during the interviews. Earlier interviews were therefore shown a (slightly) different version than the one shown below. Participants were shown an enlarged A3 print-out of the timeline, using colors to group related events to make the information more accessible.

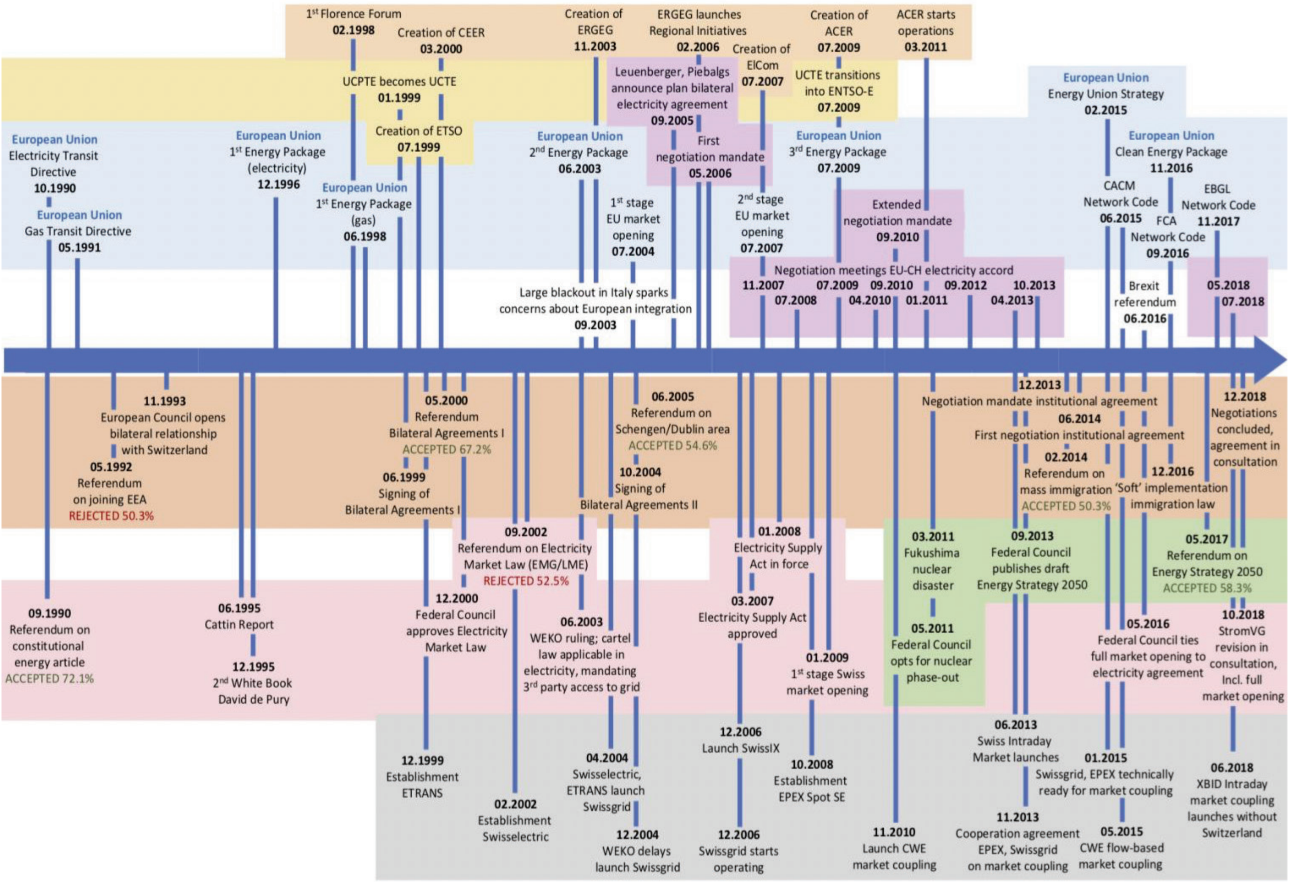

Figure C.1: Full timeline of events related to Swiss-EU energy relations.

All events are listed in chronological order below for the reader's comprehension:

1990.09	Referendum on constitutional energy article. ACCEPTED 72.5%.
1990.10	European Union. Electricity Transit Directive.
1991.05	European Union. Gas Transit Directive.
1992.05	Referendum on joining EEA. REJECTED 50.3%.
1993.11	European Council opens bilateral relationship with Switzerland.
1995.06	Cattin Report.
1995.12	2nd White Book David de Pury.
1996.12	European Union. 1st Energy Package (electricity).
1998.02	1st Florence Forum.
1998.06	European Union. 1st Energy Package (gas).
1999.01	UCPTE becomes UCTE.
1999.06	Signing of Bilateral Agreements I.

1999.07	Creation of ETSO.
1999.12	Establishment ETRANS.
2000.03	Creation of CEER.
2000.05	Referendum Bilateral Agreements I. ACCEPTED 67.2%.
2000.12	Federal Council approves Electricity Market Law.
2002.02	Establishment Swisselectric.
2002.09	Referendum on Electricity Market Law (EMG/LME). REJECTED 52.5%.
2003.05	WEKO ruling: cartel law applicable in electricity, mandating 3rd party access to grid.
2003.06	European Union. 2nd Energy Package.
2003.09	Large blackout in Italy sparks concerns about European integration.
2003.11	Creation of ERGEG.
2004.04	Swisselectric, ETRANS launch Swissgrid.
2004.07	1st stage EU market opening.
2004.12	WEKO delays launch Swissgrid.
2004.10	Signing of Bilateral Agreements II.
2005.06	Referendum on Schengen/Dublin area. ACCEPTED 54.6%.
2005.09	Leuenberger, Piebalgs announce plan bilateral electricity agreement.
2006.02	ERGEG launches Regional Initiatives.
2006.05	First negotiation mandate.
2006.12	Launch SwissIX.
2006.12	Swissgrid starts operating.
2007.03	Electricity Supply Act approved.
2007.07	2nd stage EU market opening.
2007.07	Creation of ElCom.
2007.11	Negotiation meeting EU-CH electricity accord.
2008.01	Electricity Supply Act in force.
2008.07	Negotiation meeting EU-CH electricity accord.
2008.10	Establishment EPEX Spot SE.
2009.01	1st stage Swiss market opening.
2009.07	Creation of ACER.
2009.07	European Union. 3rd Energy Package.
2009.07	Negotiation meeting EU-CH electricity accord.
2009.07	UCTE transitions into ENTSO-E.
2010.04	Negotiation meeting EU-CH electricity accord.
2010.09	Extended negotiation mandate.
2010.09	Negotiation meeting EU-CH electricity accord.
2010.11	Launch CWE market coupling.
2011.01	Negotiation meeting EU-CH electricity accord.
2011.03	ACER starts operations.
2011.03	Fukushima nuclear disaster.
2011.05	Federal Council opts for nuclear phase-out.
2012.09	Negotiation meeting EU-CH electricity accord.
2013.04	Negotiation meeting EU-CH electricity accord.
2013.06	Swiss Intraday Market launches.
2013.09	Federal Council publishes draft Energy Strategy 2050.
2013.10	Negotiation meeting EU-CH electricity accord.
2013.11	Cooperation agreement EPEX, Swissgrid on market coupling.
2013.12	Negotiation mandate institutional agreement.
2014.02	Referendum on mass immigration. ACCEPTED 50.3%.
2014.06	First negotiation institutional agreement.
2015.01	Swissgrid, EPEX technically ready for market coupling.
2015.02	European Union. Energy Union Strategy.
2015.05	CWE flow-based market coupling.
2015.06	CACM Network Code.

2016.05	Federal Council ties full market opening to electricity agreement.
2016.06	Brexit referendum.
2016.09	FCA Network Code.
2016.11	European Union. Clean Energy Package.
2016.12	‘Soft’ implementation immigration law.
2017.05	Referendum on Energy Strategy 2050. ACCEPTED 58.3%.
2017.11	EBGL Network Code.
2018.05	Negotiation meeting EU-CH electricity accord.
2018.06	XBID Intraday market coupling launches without Switzerland.
2018.07	Negotiation meeting EU-CH electricity accord.
2018.10	StromVG revision in consultation, incl. full market opening.
2018.12	Negotiations concluded, agreement in consultation.

D. Equations hybrid transition model.

The hybrid model was developed on the Ventity™ 2.1 for Windows software platform. It builds on the same core concepts of the SD simulation model (as shown in Appendix A, p. 125) but is based on an entirely new system of equations to accommodate for the hybrid architecture and new software environment. Being a hybrid model, the model equations are slightly more complex than the system dynamics model. Each variable (or *element*) and its corresponding equation (or *expression*) is "owned" by a model *component*: an *entity* (agent), a *collection* of entities, or an *action* (which contain equations triggered outside of the system dynamics environment by an entity). In total, there are over 880 different elements in the model, spread over 7 entities[17], 12 collections of entities[18], and 33 actions. Components are linked through *references* to other components, comprising the agent network. The model is the sum of all components, elements, and their references.

The next pages contain a table describing all expressions in the model. They are written in the proprietary language of Ventity, which should be easily understood as it is based on natural language and common logical operators, but an explanation of the language and proprietary equations can be found in the Ventity software documentation: https://ventity.biz/documentation/

The columns in the next pages indicate the following information (in this order):

1: Component	Name of the component.
2: Component Parent	If the component is a collection or an action, this column indicates which entity they group (collection) or to which entity they belong (action).
3: Component Type	Whether the component is an entity, collection, or action.
4: Element	Name of variable.
5: Element type	Variable type (stock, flow, auxiliary, attribute, etc.).
6: Expression	Equation of variable.
7: Units	Units.
8: Element properties	This describes additional properties not part of the expression but important for the functioning, such as the target component for references or the target element for collection aggregate variables.
9: Description	This section is reserved for comments and explanations.

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[17] The four entities described in Chapter 4 (Market, Supply, Demand, Investor, p. 66), and three additional entity types that are used to ensure proper functioning of the model: Model, Time, and Weather. They can be accessed by all entities and therefore function more as "landscape" processes than actual agents with a network and are therefore not described as "agents" in the essay.

[18] The collections of entities are predominantly for the supply (6) and demand (4) agents and serve to group them by (technology) type, online status, and/or owner.

Table D.1. Equations hybrid transition model.

Component	Component Parent	Component Type	Element	Element Type	Expression	Units	Element Properties	Description
Weather		Entity						
Weather		Entity	WeatherID	Attribute			key	
Weather		Entity	hydro filling grade	Auxiliary	hydro.Sum reservoir/hydro.Sum reservoir maximum	Dmnl	Value	
Weather		Entity	hydro inflow	Auxiliary	IfThenElse(Time.hydro year=14,hydro inflow 14(Time.hour of year),IfThenElse(Time.hydro year=13, hydro inflow 13(Time.hour of year),hydro inflow 12(Time.hour of year))) *hydro yearly inflow(Time.year AD) *Time.GW to MW	MW	Value	The total natural inflow over all reservoirs. Takes the average hourly inflow (as % of total yearly inflow), modifies it by a daily average (which averages to 1 over the year).
Weather		Entity	inflow	Auxiliary	ZIDZ(IfThenElse(WeatherID="hydro",hydro inflow,IfThenElse(WeatherID="waste",waste inflow,0)) , affected plants.Sum reservoir initial maximum)	MW/(MW *Hour)	Value	Total inflow over all reservoirs is here divided by reservoir capacity (largest basins get largest share). Multiply by the reservoir capacity to find inflow at plant level. Safe for non-vaulted use as only hydro and waste will get inflow.
Weather		Entity	potential multiplication factor	Auxiliary	IfThenElse(WeatherID="wind",wind utilization factor lookup(wind.Sum capacity fixed/wind maximum potential),IfThenElse(WeatherID="solar",solar utilization factor lookup(solar.Sum capacity fixed/solar maximum potential), 1))	dmnl	Value	Finds the right multiplication for the potential that is currently installed (diminishing returns to locations where to build).
Weather		Entity	production factor	Auxiliary	IfThenElse(WeatherID="ROR",IfThenElse(Time.hydro year=14,ROR flow 14(Time.hour of year),IfThenElse(Time.hydro year=13,ROR flow 13(Time.hour of year),ROR flow 12(Time.hour of year)))*ROR growth factor, IfThenElse(Time.profile year=17,production coefficient 17(Time.hour of year),IfThenElse(Time.profile year=16,production coefficient 16(Time.hour of year),production coefficient 15(Time.hour of year)))) *potential multiplication factor	dmnl	Value	
Weather		Entity	ROR growth factor	Auxiliary	ROR yearly output(Time.year AD)/ROR yearly output(Time.start year)	dmnl	Value	How much the ROR installed capacity has grown. (no investments, exogenous).
Weather		Entity	solar maximum potential	Auxiliary	19702	MW	Value	Source: Osorio (2016).
Weather		Entity	waste inflow	Auxiliary	233	MW	Value	Average hourly waste inflow, total over all plants. Based on electricity statistics for 2016 (2041 GWh per year).
Weather		Entity	wind maximum potential	Auxiliary	2282	MW	Value	Source: Osorio (2016)
Weather		Entity	hydro inflow 12	TableFunction	0,1,0,1,0,0,8760,0	Hour		Unit out = % of yearly inflow.
Weather		Entity	hydro inflow 13	TableFunction	0,1,0,1,0,0,876,0,8760,0	hour		
Weather		Entity	hydro inflow 14	TableFunction	0,8760,0,1500,0,0,8760,0	Hour		Make sure this is zero for all except hydro, especially for batteries. Percentage of yearly inflow from the hourly rate.
Weather		Entity	hydro yearly inflow	TableFunction	0,1,0,1,2015,18733,2020,18767,2025,18767,2035,18833,2050,18933	Year		Source: VSE (2012), average over 3 scenarios.
Weather		Entity	production coefficient 15	TableFunction	0,1,0,1,0,1,8760,1	hour		Value of MW per MWp, (percentage of the peak output at this hour), averaged to a year. Sum = 8760, so need to multiply by utilization factor to receive hourly production factor.

Weather		Entity	production coefficient 16	TableFunction	0,1,0,1,0,1,8760,1	hour		
Weather		Entity	production coefficient 17	TableFunction	0,8760,0,1,0,1,8760,1	Hour		Input from the Excel file. Production coefficient (multiplication for installed capacity). Hourly. Connect correct hourly value in the Plant entity. Each "weather entity" has its own dedicated type, i.e. solar or wind. Assigning the wrong weather entity to the power plant means production of 1.
Weather		Entity	ROR flow 12	TableFunction	0,1,0,1,0,0,8760,0	Hour		
Weather		Entity	ROR flow 13	TableFunction	0,1,0,1,0,0,8760,0	hour		
Weather		Entity	ROR flow 14	TableFunction	0,1,0,1,0,0,8760,0	hour		
Weather		Entity	ROR yearly output	TableFunction	0,1,0,1,2015,16400,2020,16700,2025,16933,2035,17533,2050,18333	Year		The total ROR production for a year.
Weather		Entity	solar utilization factor lookup	TableFunction	0,1,0,1,0,0.147,0.0367,0.1358,0.9306,0.114155,1,0.100114	dmnl		
Weather		Entity	wind utilization factor lookup	TableFunction	0,1,0,1,0,0.3196,0.181,0.2497,0.195,0.2457,0.267,0.2301,1,0.1608	dmnl		
Weather		Entity	Sum yearly prod fac	Stock	0			
Weather		Entity	hydro in	Flow	production factor		Inflow (Sum yearly prod fac)	
Weather		Entity	affected plants	Reference	Condition: type WeatherID		Target Type: Supply[type]	
Weather		Entity	hydro	Reference	Condition: type "hydro"		Target Type: Supply[type]	
Weather		Entity	Model	Reference			Target Type: Model	
Weather		Entity	solar	Reference	Condition: type "solar"		Target Type: Supply[type]	
Weather		Entity	Time	Reference			Target Type: Time	
Weather		Entity	wind	Reference	Condition: type "wind"		Target Type: Supply[type]	
Weather[]	Weather	Collection						
Weather[]	Weather	Collection	Count	Auxiliary		dmnl	Value	Built-in variable. Reports the number of entities of this type existing at the end of each time slice.
Time		Entity						
Time		Entity	agreement year	Auxiliary	2050	Year	Constant Value	Either quick (2020), late (2030), or never (>2035, e.g. 2050).
Time		Entity	allow economic decommissioning	Auxiliary	0	1	Value	1= yes, 0 = no
Time		Entity	allow fuel storage reserve	Auxiliary	0	1	Constant Value	1 = yes, 0 = no. Basically whether it allows waste/gas/nuclear into the storage, or only hydro/batteries. Not yet implemented
Time		Entity	allow investments	Auxiliary	1	dmnl	Constant Value	
Time		Entity	allow mothballing	Auxiliary	1	1	Constant Value	Whether or not to allow mothballing. 1 = yes, 2 = no.
Time		Entity	allow renovation	Auxiliary	1	1	Constant Value	Whether or not to allow plants to be renovated. 1 = yes, 2 = no.
Time		Entity	allow technical decommissioning	Auxiliary	1	1	Value	1 = yes. 0 = no.
Time		Entity	BES scenario	Auxiliary	3	Dmnl	Constant Value	1=low, 2=high, 3=zero.

Time		Entity	c	Auxiliary	1	hour	Value	Used to correct the units in flows that are actually actions adding to a stock.
Time		Entity	carbon price	Auxiliary	carbon price lookup(year AD)*EUR to CHF	CHF/TC	Value	
Time		Entity	day of year	Auxiliary	Floor(hour of year/hours per day)	day	Value	
Time		Entity	demand growth percentage	Auxiliary	1	Dmnl	Constant Value	In percentage (i.e. 1 = 1% per year growth). For in demand scenario 4.
Time		Entity	demand scenario	Auxiliary	3	1	Constant Value	1 = low, 2 = mid, 3 = high. Default is mid. 4 = growing percentile based.
Time		Entity	DR scenario	Auxiliary	3	Dmnl	Constant Value	1=low, 2=high, 3=0.
Time		Entity	enable reserve	Auxiliary	0	1	Constant Value	0 = no, 1 = yes (dynamic), 2= yes (static, at "reserve install year").
Time		Entity	end of month	Auxiliary	IfThenElse(Hour of year=8759,1,IfThenElse(Hour of year=743,1,IfThenElse(Hour of year=1415,1,IfThenElse(Hour of year=2159,1,IfThenElse(Hour of year=2879,1,IfThenElse(Hour of year=3623,1,IfThenElse(Hour of year=4343,1,IfThenElse(Hour of year=5087,1,IfThenElse(Hour of year=5831,1,IfThenElse(Hour of year=6551,1,IfThenElse(Hour of year=7295,1,IfThenElse(Hour of year=8015,1,0))))))))))))	dmnl	Value	
Time		Entity	end of winter	Auxiliary	IfThenElse(hour of year=2159,1,0)	Dmnl	Value	A pulse when winter ends (last hour of March). For winter statistics.
Time		Entity	EUR to CHF	Auxiliary	1.13094	CHF/EUR	Value	Google, Dec 21, 2018.
Time		Entity	foreign price scenario	Auxiliary	1	dmnl	Constant Value	1 = low, 2 = medium, 3 = high. 2018 average, growing/stable/shrinking by 1.5% per year, at 2% convergence (i.e. towards the mean of IT/FR/DE). 0 = very low (-3) 1 = low (-1.5) 2 = medium (0) 3 = high (+1.5) 4 = very high (+3)
Time		Entity	gas price	Auxiliary	gas fuel price lookup(year AD)*EUR to CHF	CHF/(MW *hour)	Value	
Time		Entity	GW to MW	Auxiliary	1000	MW/GW	Value	Multiply GW by this factor to get MW
Time		Entity	hour of day	Auxiliary	Modulo(hour of simulation,24)	hour	Value	
Time		Entity	hour of year	Auxiliary	Modulo(hour of simulation,8760)	Hour	Value	
Time		Entity	hours per day	Auxiliary	24	Hour/day	Value	
Time		Entity	hours per year	Auxiliary	8760	Hour	Value	
Time		Entity	hydro year	Auxiliary	Floor(Modulo(year AD-2018,3))+12	1	Value	Values 12/13/14. Used for ROR / hydro inflow.
Time		Entity	import FOR	Auxiliary	IfThenElse(year AD<=agreement year,import FOR 1(year AD),0.04)	Dmnl	Value	
Time		Entity	import limit scenario	Auxiliary	2	Dmnl	Constant Value	1 = limit scenario 1, 2 = limit scenario 2, 3 = no limit (from the flat reduction)
Time		Entity	month of year	Auxiliary	IfThenElse(Hour of year<744,1,IfThenElse(Hour of year<1416,2,IfThenElse(Hour of year<2160,3,IfThenElse(Hour of year<2880,4,IfThenElse(Hour of year<3624,5,IfThenElse(Hour of year<4344,6,IfThenElse(Hour of year<5088,7,IfThenElse(Hour of year<5832,8,IfThenElse(Hour of year<6552,9,IfThenElse(Hour of year<7296,10,IfThenElse(Hour of year<8016,11,12)))))))))))	month	Value	
Time		Entity	MW to kW	Auxiliary	1000	kW/MW	Value	
Time		Entity	NTC limit factor	Auxiliary	IfThenElse(year AD<=agreement year,IfThenElse(import limit scenario=1,import limit 1(year AD),IfThenElse(import limit scenario =2,import limit 2(year AD),1)),1)	Dmnl	Value	Multiplication factor for all NTC values, proxy for reduction in import possibilities. Influenced by import limit scenario and agreement timing (which assumes all import possibilities become available).

Time		Entity	NTC scenario	Auxiliary	1	1	Value	1 = low, 2 = high (TYNDP).
Time		Entity	nuclear price	Auxiliary	nuclear fuel price lookup(year AD)*USD to CHF	CHF/(MW *hour)	Value	
Time		Entity	profile year	Auxiliary	Floor(Modulo(year AD-2018,3))+15	year	Value	15-17 (means e.g.2015). Used for all profiles, i.e. foreign prices, NTC, CH demand, weather data (solar/wind), except hydro inflow. In this case, it ranges through all 3 profiles consecutively and starts again.
Time		Entity	RES scenario	Auxiliary	0	Dmnl	Constant Value	0 = no RES support, 1= full RES support for ES50 goals, 2= half RES support for ES50 goals.
Time		Entity	reserve price	Auxiliary	2500	CHF/(MW *hour)	Constant Value	Set strike price for reserve here. Range: 2500; 2000; 1500; 1000; 500.
Time		Entity	reserve size	Auxiliary	1	Dmnl	Constant Value	1 = small (1), 2 = mid(5), 3 = midlarge (10), 4=large(15)
Time		Entity	reserve start year	Auxiliary	2020	Year	Constant Value	Year at which the strategic reserve is initiated. Only if set to static ("enable strategic reserve" = 2).
Time		Entity	start of month	Auxiliary	IfThenElse(Hour of year=0,1,IfThenElse(Hour of year=744,1,IfThenElse(Hour of year=1416,1,IfThenElse(Hour of year=2160,1,IfThenElse(Hour of year=2880,1,IfThenElse(Hour of year=3624,1,IfThenElse(Hour of year=4344,1,IfThenElse(Hour of year=5088,1,IfThenElse(Hour of year=5832,1,IfThenElse(Hour of year=6552,1,IfThenElse(Hour of year=7296,1,IfThenElse(Hour of year=8016,1,0))))))))))))	dmnl	Value	
Time		Entity	start year	Auxiliary	2018	Year	Value	
Time		Entity	USD to CHF	Auxiliary	0.991385	CHF/$	Value	Google, Dec 21, 2018
Time		Entity	year AD	Auxiliary	year of simulation+start year	Year	Value	
Time		Entity	year of simulation	Auxiliary	Floor(year)	year	Value	
Time		Entity	carbon price lookup	TableFunction	2017,2050,0,74,2017,9,2020,15,2025,22,2030,33,2035,42,2050,73	year		From SFOE 2017 adequacy study. Last point is my own extrapolation. In EUR, still need to convert.
Time		Entity	gas fuel price lookup	TableFunction	2015,2051,0,94,2017,47.333,2020,54.906,2025,58.693,2030,62.479,2035,70.053,2050,92.773	Year		From SFOE 2017 adequacy study. Original in fuel price, converted to price per mwh electricity (52.817% efficient, from NREL 2018 ATB). Up to 2035; last point my own.
Time		Entity	import FOR 1	TableFunction	2015,2036,-1,1,2018,0.3,2030,0.3,2035,0.3	Year		60%/70% reduction by 2030/2035, of which half is predictable (thus from this variable).
Time		Entity	import limit 1	TableFunction	2015,2051,0,1.5,2019,1,2020,0.8,2030,0.8,2035,0.8	Year		60%/70% reduction by 2030/2035, of which half is predictable (thus from this variable).
Time		Entity	import limit 2	TableFunction	2015,2051,0,2,2019,1,2020,0.7,2030,0.7,2050,0.7	Year		
Time		Entity	nuclear fuel price lookup	TableFunction	0,2051,0,16,2015,7,2030,7,2050,7	Year		From NREL ATB (2018). In $/MWh
Time		Entity	hour of simulation	Stock	0	hour		
Time		Entity	time flow hour	Flow	1	hour/hour	Inflow (hour of simulation)	
Time		Entity	year	Stock	0	year		
Time		Entity	time flow year	Flow	1/8760	year/hour	Inflow (year)	
Supply		Entity						
Supply		Entity	country	Attribute	"CH"			Four options: "CH", "IT", "FR", "DE". Used for import price calculation (import is modeled as a supply option), as well as

								import contracts (multiple entities in a single country compete for import capacity).
Supply		Entity	demand link	Attribute	"demand_0"			Links to demand used for country/storage plants. Links to Demand|0 as standard, should not be used if not the corresponding type.
Supply		Entity	investor	Attribute	"investor_0"			
Supply		Entity	status	Attribute	"Off"			
Supply		Entity	SupplyID	Attribute			key	
Supply		Entity	type	Attribute	"gas"			"gas", "wind", "nuclear", "solar", "hydro", "ROR","trade", "contract", "ENS".
Supply		Entity	weather	Attribute	"none"			
Supply		Entity	bidding capacity	Auxiliary	IfThenElse(type="trade",import capacity,capacity available)*IfThenElse(in maintenance>0,0,1)*forced outage	MW	Value	
Supply		Entity	bidding price	Auxiliary	IfThenElse(type="trade",import price,IfThenElse(type="ENS",market.price cap,opportunity cost))	CHF/(MW *hour)	Value	ENS = energy not served (i.e. blackout).
Supply		Entity	can be renovated	Auxiliary	IfThenElse((type="gas") OR (type="ROR") OR (type="wind") OR (type="solar") OR (type="nuclear"),IfThenElse(capacity fixed>0,1,0),0)	1	Value	Need to check
Supply		Entity	can be turned off	Auxiliary	IfThenElse((type="gas") OR (type="nuclear"),IfThenElse((capacity fixed)>0, 1, 0),0)	1	Value	
Supply		Entity	capacity available	Auxiliary	if(reservoir finite=0) {capacity fixed*weather.production factor} else {min(capacity fixed,reservoir)}	MW	Value	
Supply		Entity	capacity constructed	Auxiliary	capacity fixed+capacity mothballed	MW	Value	
Supply		Entity	capacity fixed	Auxiliary	capacity installed 1+capacity installed 2+capacity installed 3+capacity installed	MW	Value	
Supply		Entity	capacity fixed 1	Auxiliary	capacity installed+capacity installed 3+capacity installed 2+IfThenElse((time construction-age)<1,capacity in construction,0)	MW	Value	Fixed capacity one year from now.
Supply		Entity	capacity fixed 2	Auxiliary	capacity installed 3+capacity installed+IfThenElse((time construction-age)<2,capacity in construction,0)	MW	Value	Fixed capacity two years from now.
Supply		Entity	capacity fixed 3	Auxiliary	capacity installed+IfThenElse((time construction-age)<3,capacity in construction,0)	MW	Value	Fixed capacity three years from now.
Supply		Entity	derated capacity	Auxiliary	if(type="trade") {import NTC max} else {capacity fixed*derating factor}	MW	Value	Need to check if this works for all supply types, and whether to use peak or max.
Supply		Entity	derated capacity 1	Auxiliary	if(type="trade") {derated capacity} else {capacity fixed 1*derating factor}	MW	Value	Derated capacity one year from now
Supply		Entity	derated capacity 2	Auxiliary	if(type="trade") {derated capacity} else {capacity fixed 2*derating factor}	MW	Value	Derated capacity two years from now
Supply		Entity	derated capacity 3	Auxiliary	if(type="trade") {derated capacity} else {capacity fixed 3*derating factor}	MW	Value	Derated capacity three years from now
Supply		Entity	emissions	Auxiliary	emissions factor*capacity operating	TC/hour	Value	
Supply		Entity	emissions cost	Auxiliary	time.carbon price*emissions factor	CHF/(MW *hour)	Value	
Supply		Entity	filling grade	Auxiliary	ZIDZ(reservoir,reservoir maximum)	dmnl	Value	
Supply		Entity	five year profitability	Auxiliary	((((time.year AD+1)*price trend slope+price trend constant)-marginal cost)/(1+investor.discount rate)+ (((time.year AD+2)*price trend slope+price trend constant)-marginal cost)/(1+investor.discount rate)^2+ (((time.year AD+3)*price trend slope+price trend constant)-marginal	CHF	Value	NPV of 5 year operations, discounted by the investor (no risk factor, as there is no investment). Used for decommissioning and

					cost)/(1+investor.discount rate)^3+ (((time.year AD+4)*price trend slope+price trend constant)-marginal cost)/(1+investor.discount rate)^4+ (((time.year AD+5)*price trend slope+price trend constant)-marginal cost)/(1+investor.discount rate)^5) *time.hours per year*utilization factor*capacity fixed -yearly avoidable costs*(1+1/(1+investor.discount rate)+1/(1+investor.discount rate)^2+1/(1+investor.discount rate)^3+1/(1+investor.discount rate)^4+1/(1+investor.discount rate)^5)			
Supply		Entity	forced outage	Auxiliary	IfThenElse((type!="ENS"),IfThenElse(outage timer>0,0,1),1)	Dmnl	Value	0 if the plant is out, 1 if not. Multiplies the bidding capacity (i.e., normal capacity unless it is out). Excludes ENS.
Supply		Entity	forced outage rate effective	Auxiliary	IfThenElse(country!="CH",max(forced outage rate,time.import FOR),forced outage rate)	-	Value	Takes a higher FOR for units not located in CH; depending on the deal with the EU.
Supply		Entity	fuel cost	Auxiliary	IfThenElse(type="nuclear",Time.nuclear price,IfThenElse(type="gas",Time.gas price,0))+emissions cost	CHF/(MW*hour)	Value	
Supply		Entity	import capacity	Auxiliary	IfThenElse(Time.profile year=15,import NTC multiplier 15(Time.hour of year),IfThenElse(Time.profile year=16,import NTC multiplier 16(Time.hour of year),import NTC multiplier 17(Time.hour of year))) * IfThenElse(Time.NTC scenario=1,import NTC scenario 1(Time.year AD),import NTC scenario 2(Time.year AD)) *time.NTC limit factor *forced outage	MW	Value	Gets used also for NTC, in market actions.
Supply		Entity	import fee	Auxiliary	1	$/(MW*hour)	Value	Needed to differentiate from export price. If it is higher, that means you won't import to meet export demand on the same border. Lower means you can do that, i.e., unrealistic.
Supply		Entity	import NTC max	Auxiliary	if(time.NTC scenario=1) {import NTC scenario 1(time.year AD)} else {import NTC scenario 2(time.year AD)}	MW	Value	Find max number in dataset.
Supply		Entity	import price	Auxiliary	(IfThenElse(Time.profile year=15,foreign price 15(Time.hour of year),IfThenElse(Time.profile year=16,foreign price 16(Time.hour of year),foreign price 17(Time.hour of year))) * IfThenElse(Time.foreign price scenario=1,foreign price scenario 1(Time.year AD),IfThenElse(Time.foreign price scenario=2,foreign price scenario 2(Time.year AD),IfThenElse(Time.foreign price scenario=3,foreign price scenario 3(Time.year AD),IfThenElse(Time.foreign price scenario=4,foreign price scenario 4(Time.year AD),IfThenElse(Time.foreign price scenario=0,foreign price scenario 0(Time.year AD),0))))) +import fee) *time.EUR to CHF	CHF/(MW*hour)	Value	Reverts to 0 if Time.foreign price scenario is not 0-4.
Supply		Entity	marginal cost	Auxiliary	fuel cost+cost operating variable*time.USD to CHF	CHF/(MW*hour)	Value	
Supply		Entity	mean time to repair	Auxiliary	67	Hour	Value	Mohanta (2004) shows range of 96-67 hours, depending on the age and other characteristics of the plant. We use 67 as a conservative estimate.
Supply		Entity	next year profitability	Auxiliary	-yearly avoidable costs+capacity constructed*utilization factor*time.hours per year*(-marginal cost+((time.year AD+1)*price trend slope+price trend constant))	CHF	Value	
Supply		Entity	operating time remaining	Auxiliary	time maximum life-age	year	Value	How much time left.

Supply		Entity	opportunity cost	Auxiliary	IfThenElse(reservoir<(reserved amount*1.01),market.reserve strike price, (investor.reference price-marginal cost) * (1-XIDZ(reservoir-reserved amount-min(capacity fixed*time.c,reservoir-reserved amount)/2,reservoir maximum-reserved amount,1)) + marginal cost)	CHF/(MW *hour)	Value	If the amount of energy is less than the reserved amount, the price is the strike price. Otherwise, it checks the current filling-grade of the non-reserved portion of the energy and ranges it from the marginal cost to 3 times the reference price.
Supply		Entity	opportunity cost storage	Auxiliary	IfThenElse(reservoir<reserved amount,market.reserve strike price/storage efficiency, ((investor.reference price-marginal cost) * (1-XIDZ(reservoir-reserved amount+min(reservoir maximum-reservoir,capacity fixed*storage efficiency*time.c)/2,reservoir maximum-reserved amount,1)) + marginal cost)*storage efficiency)	CHF/(MW *hour)	Value	Takes the average opportunity value of energy for the next block being purchased based on the reference price. Higher than opportunity cost because of efficiency losses.
Supply		Entity	price trend constant	Auxiliary	((price average+price average m1+price average m2+price average m3)/4)-(time.year AD-2.5)*price trend slope	CHF/(MW *hour)	Value	
Supply		Entity	price trend slope	Auxiliary	(-1.5*(price average m3-((price average+price average m1+price average m2+price average m3)/4))-0.5*(price average m2-((price average+price average m1+price average m2+price average m3)/4))+0.5*(price average m1-((price average+price average m1+price average m2+price average m3)/4))+1.5*(price average-((price average+price average m1+price average m2+price average m3)/4)))/min(time.year AD,5)	CHF/(MW *Hour)/year	Value	
Supply		Entity	renovation cost fraction	Auxiliary	0.25	1	Value	
Supply		Entity	renovation investment cost	Auxiliary	(cost investment*time.USD to CHF*time.MW to kW)*(capacity fixed*renovation cost fraction)	CHF	Value	
Supply		Entity	renovation profitability	Auxiliary	ZIDZ((five year profitability-renovation investment cost),renovation investment cost)	1	Value	Profitability index for a 5 year renovation, based on simple forecast and a renovation cost fraction as a percentage of investment cost.
Supply		Entity	reserve bid amount	Auxiliary	IfThenElse(reservoir finite=1,min(reservoir maximum,market.reserve duration*capacity fixed 1),capacity fixed 1*market.reserve duration) *dispatchable	MW*hour	Value	Only capacity available next year. Excludes intermittent RES. Finite reservoirs have a maximum they can offer, unlike infinite reservoirs (=0).
Supply		Entity	reserve bid price	Auxiliary	ZIDZ(storage cost*market.reserve duration+reserve foregone profit,reserve bid amount)	CHF/(MW *hour)	Value	The fixed cost (per MWh) of storing the energy, plus the foregone profit. For this price, the
Supply		Entity	reserve bid price winter	Auxiliary	ZIDZ(storage cost*market.reserve duration+reserve foregone profit winter,reserve bid amount)	CHF/(MW *hour)	Value	
Supply		Entity	reserve foregone profit	Auxiliary	0.5*reserve percentage*reservoir maximum*(investor.reference price-marginal cost)*reservoir finite	CHF	Value	The money the water would sell for if the investor had its way (reference price). Minus the marginal cost, as that will not have to be paid. Multiplied by finite reservoir to ensure all plants without finite resources have zero (they are not foregoing profits as they produce all year round).
Supply		Entity	reserve foregone profit winter	Auxiliary	reserve percentage*reservoir maximum*(price average winter-price average)*reservoir finite	CHF	Value	The surplus the water would sell for when sold in winter, versus spread out over the year. Basically, what the operator loses by not being able to sell its water in winter. Multiplied by reservoir finite so that this

								is zero for all infinite resources (who do not los anything).
Supply		Entity	reserve percentage	Auxiliary	ZIDZ(reserve bid amount,reservoir maximum)	1	Value	Should be between 0 and 1.
Supply		Entity	reservoir maximum	Auxiliary	reservoir initial maximum*(1-reservoir yearly degradation)^age	MW*hour	Value	
Supply		Entity	yearly avoidable costs	Auxiliary	capacity constructed*(cost operating fixed*time.MW to kW*time.USD to CHF)	CHF/year	Value	
Supply		Entity	foreign price 15	TableFunction	-1,8761,0,2,0,1,8760,1	hour		
Supply		Entity	foreign price 16	TableFunction	-1,8761,0,2,0,1,8760,1	hour		
Supply		Entity	foreign price 17	TableFunction	0,8761,0,2,0,1,8760,1	hour		
Supply		Entity	foreign price scenario 0	TableFunction	0,2051,-1,1,2015,0,2050,0	year		Very low (-3)
Supply		Entity	foreign price scenario 1	TableFunction	0,2051,0,51,2015,50,2050,50	year		
Supply		Entity	foreign price scenario 2	TableFunction	0,2051,0,51,2015,50,2050,50	year		
Supply		Entity	foreign price scenario 3	TableFunction	0,2051,0,206,2015,50,2050,50	Hour		
Supply		Entity	foreign price scenario 4	TableFunction	0,2051,-1,1,2015,0,2050,0	year		Very high (+3)
Supply		Entity	import NTC multiplier 15	TableFunction	0,8761,0,2,0,1,8760,1	hour		
Supply		Entity	import NTC multiplier 16	TableFunction	-1,87601,0,2,0,1,87600,1	hour		
Supply		Entity	import NTC multiplier 17	TableFunction	-1,8761,0,2,0,1,8760,1	hour		
Supply		Entity	import NTC scenario 1	TableFunction	0,2051,0,101,2015,50,2050,50	year		
Supply		Entity	import NTC scenario 2	TableFunction	0,2051,0,51,2015,50,2050,50	year		
Supply		Entity	age	Stock	0	year		
Supply		Entity	aging	Flow	time.time flow year*(1-ZIDZ(capacity mothballed,capacity mothballed))	year/hour	Inflow (age)	Times 0 if there is no mothballed capacity, otherwise times 1.
Supply		Entity	approved permits	Stock	0	MW		Once a permit is approved, the investor will again do a profitability check, and when it is positive, will approve the oldest project. If the permit is held for over 3 years, then it is rejected (i.e., decommissioned)
Supply		Entity	capacity in construction	Stock	0	MW		
Supply		Entity	capacity installed	Stock	0	MW		
Supply		Entity	three years left	Flow	IfThenElse(operating time remaining<=3,capacity installed,0)/time.c	MW/hour	Outflow (capacity installed)	
Supply		Entity	capacity installed 1	Stock	0	MW		
Supply		Entity	one year left	Flow	IfThenElse(operating time remaining<=1,capacity installed 2,0)/time.c	MW/hour	Inflow (capacity installed 1)	
Supply		Entity	capacity installed 2	Stock	0	MW		
Supply		Entity	two years left	Flow	IfThenElse(operating time remaining<=2,capacity installed 3,0)/time.c	MW/hour	Inflow (capacity installed 2)	

Supply		Entity	one year left	Flow	IfThenElse(operating time remaining<=1,capacity installed 2,0)/time.c	MW/hour	Outflow (capacity installed 2)	
Supply		Entity	capacity installed 3	Stock	0	MW		
Supply		Entity	three years left	Flow	IfThenElse(operating time remaining<=3,capacity installed,0)/time.c	MW/hour	Inflow (capacity installed 3)	
Supply		Entity	two years left	Flow	IfThenElse(operating time remaining<=2,capacity installed 3,0)/time.c	MW/hour	Outflow (capacity installed 3)	
Supply		Entity	capacity mothballed	Stock	0	MW		
Supply		Entity	capacity operating	Stock	0	MW		
Supply		Entity	cost investment	Stock	0	$/kW		Retains information, used for renovation purposes.
Supply		Entity	cost operating fixed	Stock	0	$/(kW*year)		
Supply		Entity	cost operating variable	Stock	0	$/(MW*hour)		
Supply		Entity	derating factor	Stock	0	1		Need to set during initialization. Used for security margin calculations. In the case of trade, calculate historically by looking at whether you import or export during peak hours.
Supply		Entity	dispatchable	Stock	1	1		1=yes, 0=no. Whether the unit can actually be controlled, used for participation in reserve, to differentiate with those without a finite reservoir but are still dispatchable (e.g. gas).
Supply		Entity	emissions factor	Stock	0	TC/(MW*hour)		TC = ton of carbon. CCGT: 0.342834 TC/MWh(el) (NREL atb 2018).
Supply		Entity	forced outage rate	Stock	0.04	Dmnl		Set during initialization. 0.04 standard, as per Binden book (p. 21). 67/(67+1608)=0.04; a standard value. only deviate for certain types,
Supply		Entity	in maintenance	Stock	0	Hour		
Supply		Entity	maintenance start	Flow	IfThenElse((time.month of year=maintenance month) AND (time.start of month=1) AND (in maintenance=0),maintenance length/time.c,0)	/hour	Inflow (in maintenance)	
Supply		Entity	maintenance countdown	Flow	IfThenElse(in maintenance>0,1,0)	/hour	Outflow (in maintenance)	Counts down.
Supply		Entity	in permitting	Stock	0	MW		
Supply		Entity	maintenance length	Stock	0	Hour		Only for nuclear. Set in entities. Should be 1.5 months (1095 hours), s.t. utilization factor comes to 10.5/12 = 87.5% (SFOE, 2015).
Supply		Entity	maintenance month	Stock	0	Dmnl		Only for nuclear. Pre-set.
Supply		Entity	mothball timer	Stock	0	Hour		Set to 8760 by the mothball start event. To countdown when mothballing ends.
Supply		Entity	mothball countdown	Flow	IfThenElse(mothball timer>0,1,0)	Hour/Hour	Outflow (mothball timer)	
Supply		Entity	outage timer	Stock	0	Hour		Time left being out.
Supply		Entity	outage start	Flow	IfThenElse(((RandomUniform(0,1)<=(forced outage rate effective/mean time to repair))AND (outage timer)=0),mean time to repair/time.c,0)	Dmnl	Inflow (outage timer)	If the plant is not already on outage, then there's a chance of forced outage.

Supply		Entity	outage countdown	Flow	IfThenElse(outage timer>0,1,0)	1/Hour	Outflow (outage timer)	Counts down.
Supply		Entity	price average	Stock	44	CHF/(MW*hour)		
Supply		Entity	price average m1	Stock	36	CHF/(MW*hour)		
Supply		Entity	price average m2	Stock	44	CHF/(MW*hour)		
Supply		Entity	price average m3	Stock	44	CHF/(MW*hour)		
Supply		Entity	price average winter	Stock	50	CHF/(MW*Hour)		Average price received for this supply option in the winter months (jan, feb, mar).
Supply		Entity	renovated	Stock	0	Dmnl		Once a plant has been renovated, it counts here. Serves as a limit for renovation.
Supply		Entity	reserved amount	Stock	0	MW*hour		The amount of energy reserved by the storage reserve. Should be set by an action. Released at end of winter, returning the reserve to normal operation.
Supply		Entity	reservoir	Stock	0	MW*hour		
Supply		Entity	inflow	Flow	demand.amount stored*storage efficiency+weather.inflow*reservoir initial maximum	MW	Inflow (reservoir)	
Supply		Entity	outflow	Flow	capacity operating*reservoir finite+max(reservoir-reservoir maximum,0)/time.c	MW	Outflow (reservoir)	
Supply		Entity	reservoir finite	Stock	0	1		1 = yes, 0 = no
Supply		Entity	reservoir initial maximum	Stock	0	MW*hour		
Supply		Entity	reservoir yearly degradation	Stock	0	1		
Supply		Entity	revenues	Stock	0	CHF		
Supply		Entity	revenues flow	Flow	market.spot price*capacity operating	CHF/hour	Inflow (revenues)	
Supply		Entity	storage cost	Stock	0	CHF/(MW*hour*hour)		Inventory cost for keeping water/fuel on supply. Need to check units
Supply		Entity	storage efficiency	Stock	.9	1		Roundtrip efficiency, because production has no efficiency losses.
Supply		Entity	storage enabled	Stock	1	1		1 = yes, 0 = no. Used whether storage demand bid is used or not.
Supply		Entity	time construction	Stock	0	year		
Supply		Entity	time maximum life	Stock	50	year		
Supply		Entity	time permitting	Stock	0	year		
Supply		Entity	utilization factor	Stock	0	1		
Supply		Entity	volume sold	Stock	0	MW*hour		
Supply		Entity	volume flow	Flow	capacity operating	MW/hour	Inflow (volume sold)	
Supply		Entity	volume winter	Stock	0	MW*hour		Set by action. Sum of supplied power Jan-Mar.
Supply		Entity	volume yearly	Stock	0	MW*hour		
Supply		Entity	demand	Reference	Condition: DemandID demand link		Target Type: Demand	
Supply		Entity	investor	Reference	Condition: InvestorID		Target Type: Investor	
Supply		Entity	market	Reference			Target Type: Market	
Supply		Entity	Model	Reference			Target Type: Model	

Supply		Entity	same plants	Reference	Condition: type type		Target Type: Supply[type]	
Supply		Entity	time	Reference			Target Type: Time	
Supply		Entity	weather	Reference	Condition: WeatherID		Target Type: Weather	
Supply		Entity	decommission trigger	Trigger	((operating time remaining<0) AND (time.allow technical decommissioning=1)) OR ((five year profitability<0) AND (time.allow economic decommissioning=1) AND (operating time remaining<10) AND (time.hour of year=8579))		Action to Invoke: decommission, When: PeriodEnd, Sequence No.: 1	Both economic decommission (only if allowed) and regular (when lifetime is up, if allowed). Need to check if this does not over estimate amount of decommissioning (because it checks every time step for 10 years). Also used for deleting permits that have not been used for too long.
Supply		Entity	mothball start trigger	Trigger	(next year profitability<0) AND (time.allow mothballing=1) AND (can be turned off=1) AND (time.hour of year=0) AND (time.year AD>2021)		Action to Invoke: mothball start, When: PeriodEnd, Sequence No.: 1	
Supply		Entity	renovate trigger	Trigger	(can be renovated=1) AND (renovation profitability>investor.renovation hurdle rate) AND (operating time remaining<2) AND (time.allow renovation=1) AND (time.hour of year=8579) AND (renovated<1)		Action to Invoke: renovate, When: PeriodEnd, Sequence No.: 1	
Supply		Entity	trigger construction finish	Trigger	(capacity in construction>0) AND (age>=time construction)		Action to Invoke: construction finish, When: PeriodStart, Sequence No.: 1	
Supply		Entity	trigger grant permit	Trigger	(in permitting>0) AND (age>=time permitting) AND (same plants.sum all approved capacity<IfThenElse(type="wind",weather.wind maximum potential,IfThenElse(type="solar",weather.solar maximum potential,same plants.sum all approved capacity*2)))		Action to Invoke: grant permit, When: PeriodStart, Sequence No.: 1	If a plant is in permitting, for long enough, and the maximum potential has not yet been reached (only for solar/wind).
Supply		Entity	trigger mothball finish	Trigger	(capacity mothballed>0) AND (mothball timer=0)		Action to Invoke: mothball finish, When: PeriodStart, Sequence No.: 1	
Supply		Entity	trigger reject permit	Trigger	((in permitting>0) AND ((age>time permitting) OR ((type="wind") AND (same plants.sum all approved capacity>weather.wind maximum potential)) OR ((type="solar") AND (same plants.sum all approved capacity>weather.solar maximum potential)))) OR ((approved permits>0) AND (age>3))		Action to Invoke: reject permit, When: PeriodStart, Sequence No.: 1	Triggers if: permit process too long, approved permit too long but not used (3 years), maximum potential is reached (wind/solar only).
Supply		Entity	update prices trigger	Trigger	time.hour of year=8759		Action to Invoke: update prices, When: PeriodStart, Sequence No.: 1	
Supply		Entity	update winter price	Trigger	time.hour of year=2159		Action to Invoke: update winter price, When: PeriodStart, Sequence No.: 1	Triggers at last hour of march.
update winter price	Supply	Action						
update winter price	Supply	Action	Invoker	Reference	Condition: SupplyID		Target Type: Supply	
update winter price	Supply	Action	Parent	Reference	Condition: SupplyID		Target Type: Supply	
update prices	Supply	Action						
update prices	Supply	Action	Invoker	Reference	Condition: SupplyID		Target Type: Supply	
update prices	Supply	Action	online plants	Reference	Condition: status "On", Condition: type Parent.type		Target Type: Supply[status,type]	

update prices	Supply	Action	Parent	Reference	Condition: SupplyID		Target Type: Supply	
update prices	Supply	Action	time	Reference			Target Type: Time	
renovate	Supply	Action						
renovate	Supply	Action	Invoker	Reference	Condition: SupplyID		Target Type: Supply	
renovate	Supply	Action	Parent	Reference	Condition: SupplyID		Target Type: Supply	
reject permit	Supply	Action						
reject permit	Supply	Action	Invoker	Reference	Condition: SupplyID		Target Type: Supply	
reject permit	Supply	Action	Parent	Reference	Condition: SupplyID		Target Type: Supply	
reject permit	Supply	Action	trigger decommission	Trigger	true		Action to Invoke: Parent.decommission, When: OnCondition, Sequence No.: 1	
mothball start	Supply	Action						
mothball start	Supply	Action	Parent●status	Attribute	"Off"			
mothball start	Supply	Action	Invoker	Reference	Condition: SupplyID		Target Type: Supply	
mothball start	Supply	Action	Parent	Reference	Condition: SupplyID		Target Type: Supply	
mothball start	Supply	Action	time	Reference			Target Type: Time	
mothball finish	Supply	Action						
mothball finish	Supply	Action	Parent●status	Attribute	"On"			
mothball finish	Supply	Action	Invoker	Reference	Condition: SupplyID		Target Type: Supply	
mothball finish	Supply	Action	Parent	Reference	Condition: SupplyID		Target Type: Supply	
grant permit	Supply	Action						
grant permit	Supply	Action	Invoker	Reference	Condition: SupplyID		Target Type: Supply	
grant permit	Supply	Action	Parent	Reference	Condition: SupplyID		Target Type: Supply	
decommission	Supply	Action						
decommission	Supply	Action	Invoker	Reference	Condition: SupplyID		Target Type: Supply	
decommission	Supply	Action	Parent	Reference	Condition: SupplyID		Target Type: Supply	
decommission	Supply	Action	trigger demand decommission	Trigger	(Parent.type="battery") AND (Parent.demand link!="none")		Action to Invoke: Parent.demand.decommission, When: OnCondition, Sequence No.: 1	Need to check
create pair	Supply	Action						
create pair	Supply	Action	newDemand●country	Attribute	"CH"			Four options: "CH", "IT", "FR", "DE".
create pair	Supply	Action	newDemand●DemandID	Attribute	Parent.SupplyID		key	
create pair	Supply	Action	newDemand●status	Attribute	"on"			On or off.
create pair	Supply	Action	newDemand●supply link	Attribute	Parent.SupplyID			Links to a supply entity, can either be a country or power plant. Uses ENS for basic case, but should not be used if it is not really a power plant.
create pair	Supply	Action	newDemand●type	Attribute	"storage"			So far: "domestic", "trade", or "storage", "DR", or "interrupt".
create pair	Supply	Action	Parent●demand link	Attribute	Parent.SupplyID			Links to demand used for country/storage plants. Links to Demand|0 as standard, should not be used if not the corresponding type.
create pair	Supply	Action	newDemand●curtailed demand	Stock		MW*hour		The amount of deficiency of energy.
create pair	Supply	Action	newDemand●demand base	Stock		MW		For DR.

create pair	Supply	Action	newDemand●demand base price	Stock		CHF/(MW *hour)		For DR.
create pair	Supply	Action	newDemand●demand met	Stock		MW		
create pair	Supply	Action	newDemand●export price smoothed SMOOTHI1 SMOOTHI	Stock				
create pair	Supply	Action	newDemand●price average yearly	Stock	Parent.price average	CHF/(MW *hour)		
create pair	Supply	Action	newDemand●revenues	Stock		CHF		
create pair	Supply	Action	newDemand●volume winter	Stock		MW*hour		
create pair	Supply	Action	newDemand●volume yearly	Stock		MW*hour		
create pair	Supply	Action	newDemand●volumes	Stock		MW*hour		
create pair	Supply	Action	Invoker	Reference	Condition: SupplyID		Target Type: Supply	
create pair	Supply	Action	newDemand	Reference	Condition: DemandID		Target Type: Demand	
create pair	Supply	Action	Parent	Reference	Condition: SupplyID		Target Type: Supply	
construction start	Supply	Action						
construction start	Supply	Action	Invoker	Reference	Condition: SupplyID		Target Type: Supply	
construction start	Supply	Action	Parent	Reference	Condition: SupplyID		Target Type: Supply	
construction finish	Supply	Action						
construction finish	Supply	Action	Parent●status	Attribute	"On"			Turns plant online, for statistical purposes.
construction finish	Supply	Action	Invoker	Reference	Condition: SupplyID		Target Type: Supply	
construction finish	Supply	Action	Parent	Reference	Condition: SupplyID		Target Type: Supply	
Supply[type]	Supply	Collection						
Supply[type]	Supply	Collection	type	Attribute			key	
Supply[type]	Supply	Collection	Count	Auxiliary		dmnl	Value	Built-in variable. Reports the number of entities of this type existing at the end of each time slice.
Supply[type]	Supply	Collection	sum all approved capacity	Auxiliary	Sum approved permits+Sum capacity in construction+Sum capacity mothballed+Sum capacity fixed	MW	Value	
Supply[type]	Supply	Collection	sum all capacity	Auxiliary	Sum capacity fixed+Sum capacity mothballed+Sum capacity in construction+Sum approved permits+Sum in permitting		Value	
Supply[type]	Supply	Collection	Average emissions factor	Aggregate	Average	TC/(MW*hour)	Target Variable: emissions factor	
Supply[type]	Supply	Collection	Average forced outage	Aggregate	Average	Dmnl	Target Variable: forced outage	
Supply[type]	Supply	Collection	Average forced outage rate effective	Aggregate	Average	-	Target Variable: forced outage rate effective	
Supply[type]	Supply	Collection	Average mean time to repair	Aggregate	Average	Hour	Target Variable: mean time to repair	
Supply[type]	Supply	Collection	Average price average	Aggregate	Average	CHF/(MW *hour)	Target Variable: price average	
Supply[type]	Supply	Collection	Average storage cost	Aggregate	Average	CHF/(MW *hour*hour)	Target Variable: storage cost	

Supply[type]	Supply	Collection	Average utilization factor	Aggregate	Average	1	Target Variable: utilization factor	
Supply[type]	Supply	Collection	Sum approved permits	Aggregate	Sum	MW	Target Variable: approved permits	
Supply[type]	Supply	Collection	Sum capacity fixed	Aggregate	Sum	MW	Target Variable: capacity fixed	
Supply[type]	Supply	Collection	Sum capacity in construction	Aggregate	Sum	MW	Target Variable: capacity in construction	
Supply[type]	Supply	Collection	Sum capacity mothballed	Aggregate	Sum	MW	Target Variable: capacity mothballed	
Supply[type]	Supply	Collection	Sum in permitting	Aggregate	Sum	MW	Target Variable: in permitting	
Supply[type]	Supply	Collection	Sum reservoir	Aggregate	Sum	MW*hour	Target Variable: reservoir	
Supply[type]	Supply	Collection	Sum reservoir initial maximum	Aggregate	Sum	MW*hour	Target Variable: reservoir initial maximum	
Supply[type]	Supply	Collection	Sum reservoir maximum	Aggregate	Sum	MW*hour	Target Variable: reservoir maximum	
Supply[type]	Supply	Collection	Sum volume winter	Aggregate	Sum	MW*hour	Target Variable: volume winter	
Supply[type]	Supply	Collection	Sum volume yearly	Aggregate	Sum	MW*hour	Target Variable: volume yearly	
Supply[status]	Supply	Collection						
Supply[status]	Supply	Collection	status	Attribute			key	
Supply[status]	Supply	Collection	Count	Auxiliary		dmnl	Value	Built-in variable. Reports the number of entities of this type existing at the end of each time slice.
Supply[status,type]	Supply	Collection						
Supply[status,type]	Supply	Collection	status	Attribute			key	
Supply[status,type]	Supply	Collection	type	Attribute			key	
Supply[status,type]	Supply	Collection	Count	Auxiliary		dmnl	Value	Built-in variable. Reports the number of entities of this type existing at the end of each time slice.
Supply[status,type]	Supply	Collection	Average utilization factor	Aggregate	Average	1	Target Variable: utilization factor	
Supply[investor,type]	Supply	Collection						
Supply[investor,type]	Supply	Collection	investor	Attribute			key	
Supply[investor,type]	Supply	Collection	type	Attribute			key	
Supply[investor,type]	Supply	Collection	Count	Auxiliary		dmnl	Value	Built-in variable. Reports the number of entities of this type existing at the end of each time slice.
Supply[investor,type]	Supply	Collection	Average utilization factor	Aggregate	Average	1	Target Variable: utilization factor	
Supply[investor,type]	Supply	Collection	Sum approved permits	Aggregate	Sum	MW	Target Variable: approved permits	

Supply[investor,type]	Supply	Collection	investor	Reference	Condition: InvestorID		Target Type: Investor	
Supply[investor,status,type]	Supply	Collection						
Supply[investor,status,type]	Supply	Collection	investor	Attribute			key	
Supply[investor,status,type]	Supply	Collection	status	Attribute			key	
Supply[investor,status,type]	Supply	Collection	type	Attribute			key	
Supply[investor,status,type]	Supply	Collection	avg x	Auxiliary	time.year AD-2.5	year	Value	
Supply[investor,status,type]	Supply	Collection	avg y	Auxiliary	(Average price average+Average price average m1+Average price average m2+Average price average m3)/4	CHF/(MW *hour)	Value	
Supply[investor,status,type]	Supply	Collection	Count	Auxiliary		dmnl	Value	Built-in variable. Reports the number of entities of this type existing at the end of each time slice.
Supply[investor,status,type]	Supply	Collection	price trend constant	Auxiliary	avg y-avg x*price trend slope	CHF/(MW *hour)	Value	
Supply[investor,status,type]	Supply	Collection	price trend slope	Auxiliary	sum dif x y/sum dif x x	CHF/(MW *hour)/year	Value	
Supply[investor,status,type]	Supply	Collection	sum dif x x	Auxiliary	5	year*year	Value	
Supply[investor,status,type]	Supply	Collection	sum dif x y	Auxiliary	(-1.5*(Average price average m3-avg y)-0.5*(Average price average m2-avg y)+0.5*(Average price average m1-avg y)+1.5*(Average price average-avg y))	year*CHF/(MW*hour)	Value	
Supply[investor,status,type]	Supply	Collection	Average fuel cost	Aggregate	Average	CHF/(MW *hour)	Target Variable: fuel cost	
Supply[investor,status,type]	Supply	Collection	Average price average	Aggregate	Average	CHF/(MW *hour)	Target Variable: price average	
Supply[investor,status,type]	Supply	Collection	Average price average m1	Aggregate	Average	CHF/(MW *hour)	Target Variable: price average m1	
Supply[investor,status,type]	Supply	Collection	Average price average m2	Aggregate	Average	CHF/(MW *hour)	Target Variable: price average m2	
Supply[investor,status,type]	Supply	Collection	Average price average m3	Aggregate	Average	CHF/(MW *hour)	Target Variable: price average m3	
Supply[investor,status,type]	Supply	Collection	Average utilization factor	Aggregate	Average	1	Target Variable: utilization factor	
Supply[investor,status,type]	Supply	Collection	investor	Reference	Condition: InvestorID		Target Type: Investor	
Supply[investor,status,type]	Supply	Collection	time	Reference			Target Type: Time	
Supply[]	Supply	Collection						
Supply[]	Supply	Collection	Count	Auxiliary		dmnl	Value	Built-in variable. Reports the number of entities of this type existing at the end of each time slice.
Supply[]	Supply	Collection	Sum capacity operating	Aggregate	Sum	MW	Target Variable: capacity operating	
Supply[]	Supply	Collection	Sum derated capacity	Aggregate	Sum	MW	Target Variable: derated capacity	
Supply[]	Supply	Collection	Sum derated capacity 3	Aggregate	Sum	MW	Target Variable: derated capacity 3	

Supply[]	Supply	Collection	Sum outage timer	Aggregate	Sum	Hour	Target Variable: outage timer	
Supply[]	Supply	Collection	Sum reserved amount	Aggregate	Sum	MW*hour	Target Variable: reserved amount	
Supply[]	Supply	Collection	Sum reservoir finite	Aggregate	Sum	1	Target Variable: reservoir finite	Amount of reservoirs (used in the R2 action)
Model		Entity						
Model		Entity	Final Time	Auxiliary	120	Hour	Constant Value	
Model		Entity	Initial Time	Auxiliary	0	Hour	Constant Value	
Model		Entity	Time	Auxiliary	0	Hour	Value	
Model		Entity	Time Step	Auxiliary	1	Hour	Constant Value	
Market		Entity						
Market		Entity	annual renewable production installed	Auxiliary	time.hours per year*(solar weather.potential multiplication factor*solar.Sum capacity fixed+wind weather.potential multiplication factor*wind.Sum capacity fixed)	MW*Hour	Value	Wind/solar production from installed capacity only (not permitted).
Market		Entity	consumer cost	Auxiliary	reserve tariff+price average yearly	CHF/(MW *Hour)	Value	The price the consumer is paying for electricity; excludes fees/taxes other than the reserve and the wholesale price.
Market		Entity	distance from target BES	Auxiliary	IfThenElse(time.BES scenario=1,BES scenario 1(time.year AD),BES scenario 2(time.year AD))-BES.Sum reservoir maximum	MW*Hour	Value	Positive: under target. Negative: over target.
Market		Entity	distance from target DR	Auxiliary	IfThenElse(time.DR scenario=1,DR scenario 1(time.year AD),DR scenario 2(time.year AD))*domestic.peak demand-DR.Sum demand base	MW	Value	Positive: under target. Negative: over target.
Market		Entity	distance from target RES	Auxiliary	ZIDZ(renewable target(time.year AD),time.RES scenario)-renewable annual production expected	MW*Hour	Value	Positive distance; below target. Negative: over target.
Market		Entity	energy independence annual	Auxiliary	ZIDZ(CH demand.Sum volume yearly-trade balance*time.GW to MW,CH demand.Sum volume yearly)	dmnl	Value	Higher than one: more export than import. Value below one means an import dependence.
Market		Entity	energy independence winter	Auxiliary	ZIDZ(CH demand.Sum volume winter-trade balance winter,CH demand.Sum volume winter)	Dmnl	Value	Higher than one: more export than import. Value below one means an import dependence.
Market		Entity	export value	Auxiliary	ExFR.volume yearly*ExFR.price average yearly+ExDE.volume yearly*ExDE.price average yearly+ExIT.volume yearly*ExIT.price average yearly	CHF	Value	
Market		Entity	export yearly	Auxiliary	ExDE.volume yearly+ExFR.volume yearly+ExIT.volume yearly	MW*hour	Value	
Market		Entity	feed in tariff	Auxiliary	50	CHF/(MW *Hour)	Value	Current level = 23. According to SFOE (2018). Supposed to reduce when PV/wind costs go down, but for the model we can keep it because it disappears when the targets are reached. Put it higher so that it actually makes wind/solar profitable.
Market		Entity	gas installed MW	Auxiliary	gas.Sum capacity fixed	MW	Value	
Market		Entity	gas production MWh	Auxiliary	gas.Sum volume yearly	MW*hour	Value	
Market		Entity	hydro yearly net production	Auxiliary	(hydro prod.Sum volume yearly-hydro cons.Sum volume yearly)/1000000	TW*hour	Value	
Market		Entity	import value	Auxiliary	ImFR.volume yearly*ImFR.price average+ImDE.volume yearly*ImDE.price average+ImIT.volume yearly*ImIT.price average+LTC.Sum volume yearly*LTC.Average price average	CHF	Value	
Market		Entity	import yearly	Auxiliary	ImDE.volume yearly+ImFR.volume yearly+ImIT.volume yearly+LTC.Sum volume yearly	MW*hour	Value	
Market		Entity	investment limit yearly	Auxiliary	1000	MW	Constant Value	Absolute maximum amount of investments possible in any year. Theoretically can be more, if the year before had less

								(and year starts at 1000), but on average this is the maximum.
Market		Entity	million multiplication	Auxiliary	1/1000000	Mio	Value	
Market		Entity	new BES capacity ratio	Auxiliary	8	(MW*Hour)/(MW)	Constant Value	Need to find source.
Market		Entity	new BES size minimum	Auxiliary	400	MW*Hour	Value	Corresponds to a 50 MW battery.
Market		Entity	new DR price	Auxiliary	500	CHF/(MW *hour)	Constant Value	
Market		Entity	new DR size minimum	Auxiliary	50	MW	Value	
Market		Entity	price cap	Auxiliary	3000	CHF/(MW *hour)	Value	Used for the ENS, sets price in case of no energy.
Market		Entity	production subsidy	Auxiliary	IfThenElse(distance from target RES>0, feed in tariff, 0)	CHF/(MW *hour)	Value	Basically, as long as the target is not reached, RES are supported.
Market		Entity	renewable annual production expected	Auxiliary	((wind.sum all approved capacity*wind.Average utilization factor)+(solar.sum all approved capacity*solar.Average utilization factor))*time.hours per year	MW*Hour	Value	Total expected renewable production.
Market		Entity	reserve cost million	Auxiliary	reserve cost*million multiplication	Mio*CHF	Value	Reserve cost in millions
Market		Entity	reserve duration	Auxiliary	168	hour	Constant Value	Time when the reserve must be online. 4 weeks = 672, 1 week = 168.
Market		Entity	reserve energy target	Auxiliary	IfThenElse(time.reserve size=1,160000,IfThenElse(time.reserve size=2,800000,IfThenElse(time.reserve size=3,1600000,2400000)))	MW*hour	Value	Minimum amount of energy to contract in the storage reserve. small = 0.16 TWh, mid = 0.8 TWh, midlarge=1.6 TWh, large = 2.4 TWh (= 160 000 / 800 000 / 1600 000 / 2400 000 MWh).
Market		Entity	reserve tariff	Auxiliary	reserve cost/domestic.annual demand	CHF/(MW *hour)	Value	Price in CHF/MWh for consumers.
Market		Entity	security margin	Auxiliary	Supply.Sum derated capacity/domestic.peak demand	1	Value	
Market		Entity	sensitivity dummy variable	Auxiliary	1	Dmnl	Constant Value	Literally anything.
Market		Entity	spot price smoothed	Auxiliary	SMOOTHI(spot price,336, price average yearly)	CHF/(MW *Hour)	Value	
Market		Entity	spot price smoothed SMOOTHI1 DelayTime	Auxiliary	336		Value	
Market		Entity	spot price smoothed SMOOTHI1 InitialValue	Auxiliary	price average yearly		Value	
Market		Entity	spot price smoothed SMOOTHI1 Input	Auxiliary	spot price		Value	
Market		Entity	total demand met	Auxiliary	Demand.Sum demand met	MW	Value	
Market		Entity	total energy not served	Auxiliary	ENS.capacity operating	MW	Value	
Market		Entity	total power supplied	Auxiliary	Supply.Sum capacity operating	MW	Value	
Market		Entity	trade balance	Auxiliary	(import yearly-export yearly)/time.GW to MW	GW*hour	Value	Import: positive. Updates yearly

Market		Entity	trade balance winter	Auxiliary	ImDE.volume winter+ImFR.volume winter+ImIT.volume winter+LTC.Sum volume winter-ExIT.volume winter-ExFR.volume winter-ExDE.volume winter	MW*hour	Value	Import: positive. Balance of trade in winter (Jan-Mar).
Market		Entity	trade value	Auxiliary	export value-import value	CHF	Value	A negative number means Switzerland spends more money abroad than it gains.
Market		Entity	trade value million	Auxiliary	trade value*million multiplication	Mio*CHF	Value	Trade value in million.
Market		Entity	VOLL	Auxiliary	10000	CHF/(MW *hour)	Value	
Market		Entity	BES scenario 1	TableFunction	2015,2041,-1,9201,2017,0,2025,2000,2040,9200	Year		Amount of energy stored in batteries. Low scenario. Based on Sossan (2018). Half of the capacity reached to get to the low reliability standard, 5 years after the RES target. See excel for calculation.
Market		Entity	BES scenario 2	TableFunction	2015,2051,-1,33674,2017,0,2025,7400,2040,33400	Year		Amount of energy stored in batteries. High scenario. Based on Sossan (2018). Full of the capacity reached to get to the high reliability standard, 5 years after the RES target. See excel for calculation
Market		Entity	DR scenario 1	TableFunction	0,2051,-1,1,2017,0,2035,0.05	Year		Percentage of peak demand that is flexible.
Market		Entity	DR scenario 2	TableFunction	0,2051,-1,1,2017,0,2035,0.1	Year		Percentage of peak demand that is flexible.
Market		Entity	renewable target	TableFunction	2015,2036,-1,11400001,2015,0,2020,4400000,2035,11400000	Year		SFOE (2018); targets of the ES50. Target for renewables outside hydro.
Market		Entity	count A	Stock	0	1		
Market		Entity	count B	Stock	0	1		
Market		Entity	count C	Stock	0	1		
Market		Entity	count D1	Stock	0	1		
Market		Entity	count D2A	Stock	0	1		
Market		Entity	count D2B	Stock	0	1		
Market		Entity	count E	Stock	0	1		
Market		Entity	counter	Stock	2	1		If you change the starting value, also change it in action E (where it resets).
Market		Entity	counter action	Stock	0	1		
Market		Entity	energy independence m1	Stock	1	1		
Market		Entity	energy independence m2	Stock	1	1		
Market		Entity	energy independence m3	Stock	1	1		
Market		Entity	ENS count	Stock	0	Dmnl		Number of times there was energy not served.
Market		Entity	ENS operating	Flow	IfThenElse(ENS.capacity operating>0,1,0)	/Hour	Inflow (ENS count)	
Market		Entity	ENS per month	Stock	0	MW*hour		
Market		Entity	accumulate ENS per month	Flow	accumulate ENS	MW	Inflow (ENS per month)	
Market		Entity	ENS percentage monthly	Stock	0	1		
Market		Entity	ENS percentage yearly	Stock	0	1		
Market		Entity	ENS volumes	Stock	0	MW*hour		
Market		Entity	accumulate ENS	Flow	total energy not served	MW	Inflow (ENS volumes)	
Market		Entity	finished loop	Stock	0	1		

Market		Entity	import capacity remaining	Stock	0	MW		Used in actions to ensure that all imported entities (from another country) respect the maximum import limit.
Market		Entity	last demand price	Stock	0	CHF/(MW *Hour)		
Market		Entity	next demand price	Stock	0	CHF/(MW *Hour)		
Market		Entity	price average monthly	Stock	50	CHF/(MW *hour)		
Market		Entity	price average yearly	Stock	44.288	CHF/(MW *hour)		
Market		Entity	price average yearly m1	Stock	36.085	CHF/(MW *hour)		
Market		Entity	price average yearly m2	Stock	40.96	CHF/(MW *hour)		
Market		Entity	price average yearly m3	Stock	40	CHF/(MW *hour)		
Market		Entity	R1	Stock	0	Dmnl		
Market		Entity	R2	Stock	0	Dmnl		
Market		Entity	R3	Stock	0	Dmnl		
Market		Entity	R4	Stock	0	Dmnl		
Market		Entity	remaining investments	Stock	investment limit yearly	MW		
Market		Entity	investment space increase	Flow	ifthenelse(remaining investments<2*investment limit yearly,investment limit yearly/time.hours per year,0)	MW/hour	Inflow (remaining investments)	
Market		Entity	reserve cost	Stock	0	CHF		Set by R3 action. Full cost of the reserve (money paid out to the operators).
Market		Entity	reserve count	Stock	0	Hour		Counts how many hours per year the SR is operating. Reset by action (update yearly).
Market		Entity	reserve operating	Flow	IfThenElse(spot price=reserve strike price,1,0)	Dmnl	Inflow (reserve count)	Adds 1 to the count every time the reserve is operating.
Market		Entity	reserve hours	Stock	0	Hour		Updated by action (update yearly). How many hours (last year) the SR was operating.
Market		Entity	reserve size	Stock	0	MW*Hour		Used for process list action.
Market		Entity	reserve strike price	Stock	2500	CHF/(MW *Hour)		The price at which the reserved water/energy bids into the market, i.e. is released. Set administratively or in an action. Effectively a scarcity cap, needs to be higher than the market.
Market		Entity	correct price	Flow	time.reserve price-reserve strike price	CHF/(MW *hour)/hour	Inflow (reserve strike price)	Crutch; simply updates the reserve strike price to be correct. Did not want to alter model structure.
Market		Entity	revenues	Stock	0	CHF		
Market		Entity	accumulate revenues	Flow	total power supplied*spot price	CHF/hour	Inflow (revenues)	
Market		Entity	revenues per month	Stock	0	CHF		
Market		Entity	accumulate revenues per month	Flow	accumulate revenues	CHF/hour	Inflow (revenues per month)	
Market		Entity	shortage hours	Stock	0	Hour		Updated by action (update yearly). Counts how many hours there was a shortage of electricity (last year).

Market		Entity	spot price	Stock	0	CHF/(MW *hour)		
Market		Entity	spot price smoothed SMOOTHI1 SMOOTHI	Stock	spot price smoothed SMOOTHI1 InitialValue			
Market		Entity	spot price smoothed SMOOTHI1 FlowIn	Flow	(spot price smoothed SMOOTHI1 Input - spot price smoothed SMOOTHI1 SMOOTHI)/spot price smoothed SMOOTHI1 DelayTime		Inflow (spot price smoothed SMOOTHI1 SMOOTHI)	
Market		Entity	sum demand options	Stock	0	MW		
Market		Entity	total supplied	Stock	0	1		
Market		Entity	volumes	Stock	0	MW*hour		
Market		Entity	accumulate volumes	Flow	total power supplied	MW	Inflow (volumes)	
Market		Entity	volumes per month	Stock	0	MW*hour		
Market		Entity	accumulate volumes per month	Flow	accumulate volumes	MW	Inflow (volumes per month)	
Market		Entity	BES	Reference	Condition: type "battery"		Target Type: Supply[type]	
Market		Entity	CH demand	Reference	Condition: country "CH"		Target Type: Demand[country]	
Market		Entity	Demand	Reference			Target Type: Demand[]	
Market		Entity	Demand_on	Reference	Condition: status "on"		Target Type: Demand[status]	
Market		Entity	domestic	Reference	Condition: DemandID "domestic"		Target Type: Demand	
Market		Entity	DR	Reference	Condition: type "DR"		Target Type: Demand[type]	
Market		Entity	ENS	Reference	Condition: SupplyID "ENS"		Target Type: Supply	
Market		Entity	ExDE	Reference	Condition: DemandID "DE"		Target Type: Demand	
Market		Entity	ExFR	Reference	Condition: DemandID "FR"		Target Type: Demand	
Market		Entity	ExIT	Reference	Condition: DemandID "IT"		Target Type: Demand	
Market		Entity	gas	Reference	Condition: type "gas"		Target Type: Supply[type]	
Market		Entity	hydro cons	Reference	Condition: type "storage"		Target Type: Demand[type]	
Market		Entity	hydro prod	Reference	Condition: type "hydro"		Target Type: Supply[type]	
Market		Entity	ImDE	Reference	Condition: SupplyID "DE"		Target Type: Supply	
Market		Entity	ImFR	Reference	Condition: SupplyID "FR"		Target Type: Supply	
Market		Entity	ImIT	Reference	Condition: SupplyID "IT"		Target Type: Supply	
Market		Entity	LTC	Reference	Condition: type "contract"		Target Type: Supply[type]	
Market		Entity	Model	Reference			Target Type: Model	
Market		Entity	solar	Reference	Condition: type "solar"		Target Type: Supply[type]	

Market		Entity	solar weather	Reference	Condition: WeatherID "solar"		Target Type: Weather	
Market		Entity	Supply	Reference			Target Type: Supply[]	
Market		Entity	Supply_on	Reference	Condition: status "on"		Target Type: Supply[status]	
Market		Entity	time	Reference			Target Type: Time	
Market		Entity	wind	Reference	Condition: type "wind"		Target Type: Supply[type]	
Market		Entity	wind weather	Reference	Condition: WeatherID "wind"		Target Type: Weather	
Market		Entity	trigger clear market	Trigger	((Model.Time>=0) AND (true)) OR (Model.Time=5)		Action to Invoke: A_clear market, When: PeriodStart, Sequence No.: 1	
Market		Entity	trigger invest BES	Trigger	(distance from target BES>new BES size minimum) AND (time.BES scenario!=3)		Action to Invoke: invest BES, When: PeriodStart, Sequence No.: 1	
Market		Entity	trigger invest DR	Trigger	(distance from target DR>=new DR size minimum) AND (time.DR scenario!=3)		Action to Invoke: invest DR, When: PeriodStart, Sequence No.: 1	Creates a DR demand agent that has the size to reach the target.
Market		Entity	trigger reserve	Trigger	(time.enable reserve=1) AND (time.year AD>=time.reserve start year) AND (time.month of year=10) AND (time.start of month=1)		Action to Invoke: R1_start reserve, When: PeriodStart, Sequence No.: 1	Triggered on October 1st (t=6552). Reserve the energy for feb-march, until end of march (t=2879).
Market		Entity	trigger update monthly	Trigger	time.end of month=1		Action to Invoke: update monthly, When: PeriodStart, Sequence No.: 1	
Market		Entity	trigger update yearly	Trigger	time.hour of year=8759		Action to Invoke: update yearly, When: PeriodStart, Sequence No.: 1	
Market		Entity	turn reserve off	Trigger	(Supply.Sum reserved amount>0) AND (time.start of month=1) AND (time.month of year=4)		Action to Invoke: R4_clear reserve, When: PeriodStart, Sequence No.: 1	1st of April it decommisisons any and all reserve.
update yearly	Market	Action						
update yearly	Market	Action	Invoker	Reference			Target Type: Market	
update yearly	Market	Action	Parent	Reference			Target Type: Market	
update yearly	Market	Action	Parent.CH demand	Reference	Condition: country "CH"		Target Type: Demand[country]	
update monthly	Market	Action						
update monthly	Market	Action	Invoker	Reference			Target Type: Market	
update monthly	Market	Action	Parent	Reference			Target Type: Market	
R4_clear reserve	Market	Action						
R4_clear reserve	Market	Action	Invoker	Reference			Target Type: Market	
R4_clear reserve	Market	Action	Parent	Reference			Target Type: Market	
R4_clear reserve	Market	Action	refSupply	Reference	Condition: SupplyID		Target Type: Supply	
R3_calculate cost	Market	Action						
R3_calculate cost	Market	Action	count	Stock	1	Dmnl		
R3_calculate cost	Market	Action	select only first	Flow	1	dmnl	Outflow (count)	
R3_calculate cost	Market	Action	Invoker	Reference			Target Type: Market	

R3_calculate cost	Market	Action	Parent	Reference			Target Type: Market	
R3_calculate cost	Market	Action	refSupply	Reference	Condition: SupplyID		Target Type: Supply	
R2_set reserves	Market	Action						
R2_set reserves	Market	Action	count	Stock	Supply.Count	Dmnl		
R2_set reserves	Market	Action	countdown	Flow	1	Dmnl	Outflow (count)	
R2_set reserves	Market	Action	Invoker	Reference			Target Type: Market	
R2_set reserves	Market	Action	Parent	Reference			Target Type: Market	
R2_set reserves	Market	Action	refSupply	Reference	Condition: SupplyID		Target Type: Supply	
R2_set reserves	Market	Action	supply	Reference			Target Type: Supply[]	
R2_set reserves	Market	Action	trigger R3	Trigger	count=0		Action to Invoke: Parent.R3_calculate cost, When: OnCondition, Sequence No.: 1	
R1_start reserve	Market	Action						
R1_start reserve	Market	Action	Invoker	Reference			Target Type: Market	
R1_start reserve	Market	Action	Parent	Reference			Target Type: Market	
R1_start reserve	Market	Action	trigger R2	Trigger	true		Action to Invoke: Parent.R2_set reserves, When: OnCondition, Sequence No.: 1	
invest DR	Market	Action						
invest DR	Market	Action	newDemand●country	Attribute	"CH"			Four options: "CH", "IT", "FR", "DE".
invest DR	Market	Action	newDemand●DemandID	Attribute			key	
invest DR	Market	Action	newDemand●status	Attribute	"on"			On or off.
invest DR	Market	Action	newDemand●supply link	Attribute	"ENS"			Links to a supply entity, can either be a country or power plant. Uses ENS for basic case, but should not be used if it is not really a power plant.
invest DR	Market	Action	newDemand●type	Attribute	"DR"			So far: "domestic", "trade", or "storage", "DR", or "interrupt".
invest DR	Market	Action	newDemand●curtailed demand	Stock		MW*hour		The amount of deficiency of energy.
invest DR	Market	Action	newDemand●demand base	Stock	Parent.distance from target DR	MW		For DR.
invest DR	Market	Action	newDemand●demand base price	Stock	Parent.new DR price	CHF/(MW*hour)		For DR.
invest DR	Market	Action	newDemand●demand met	Stock		MW		
invest DR	Market	Action	newDemand●export price smoothed SMOOTHI1 SMOOTHI	Stock				
invest DR	Market	Action	newDemand●price average yearly	Stock		CHF/(MW*hour)		
invest DR	Market	Action	newDemand●revenues	Stock		CHF		
invest DR	Market	Action	newDemand●volume winter	Stock		MW*hour		

invest DR	Market	Action	newDemand●volume yearly	Stock		MW*hour		
invest DR	Market	Action	newDemand●volumes	Stock		MW*hour		
invest DR	Market	Action	Invoker	Reference			Target Type: Market	
invest DR	Market	Action	newDemand	Reference	Condition: DemandID		Target Type: Demand	
invest DR	Market	Action	Parent	Reference			Target Type: Market	
invest BES	Market	Action						
invest BES	Market	Action	newSupply●country	Attribute	"CH"			Four options: "CH", "IT", "FR", "DE". Used for import price calculation (import is modeled as a supply option), as well as import contracts (multiple entities in a single country compete for import capacity).
invest BES	Market	Action	newSupply●demand link	Attribute	"demand_0"			Links to demand used for country/storage plants. Links to Demand|0 as standard, should not be used if not the corresponding type.
invest BES	Market	Action	newSupply●investor	Attribute	"investor_0"			
invest BES	Market	Action	newSupply●status	Attribute	"On"			
invest BES	Market	Action	newSupply●SupplyID	Attribute	"BES"		key	
invest BES	Market	Action	newSupply●type	Attribute	"battery"			"gas", "wind", "nuclear", "solar", "hydro", "ROR","trade", "contract", "ENS".
invest BES	Market	Action	newSupply●weather	Attribute	"none"			
invest BES	Market	Action	newSupply●age	Stock		year		
invest BES	Market	Action	newSupply●approved permits	Stock		MW		
invest BES	Market	Action	newSupply●capacity in construction	Stock		MW		
invest BES	Market	Action	newSupply●capacity installed	Stock	Parent.distance from target BES/Parent.new BES capacity ratio	MW		
invest BES	Market	Action	newSupply●capacity installed 1	Stock		MW		
invest BES	Market	Action	newSupply●capacity installed 2	Stock		MW		
invest BES	Market	Action	newSupply●capacity installed 3	Stock		MW		
invest BES	Market	Action	newSupply●capacity mothballed	Stock		MW		
invest BES	Market	Action	newSupply●capacity operating	Stock		MW		
invest BES	Market	Action	newSupply●cost investment	Stock		$/kW		Retains information, used for renovation purposes.
invest BES	Market	Action	newSupply●cost operating fixed	Stock		$/(kW*year)		
invest BES	Market	Action	newSupply●cost operating variable	Stock		$/(MW*hour)		
invest BES	Market	Action	newSupply●derating factor	Stock		1		Need to set during initialization. Used for security margin calculations. In the case

								of trade, calculate historically by looking at whether you import or export during peak hours.
invest BES	Market	Action	newSupply●dispatchable	Stock	1	1		1=yes, 0=no. Whether the unit can actually be controlled, used for participation in reserve, to differentiate with those without a finite reservoir but are still dispatchable (e.g. gas).
invest BES	Market	Action	newSupply●emissions factor	Stock		TC/(MW*hour)		TC = ton of carbon.
invest BES	Market	Action	newSupply●forced outage rate	Stock		Dmnl		
invest BES	Market	Action	newSupply●in maintenance	Stock		Hour		
invest BES	Market	Action	newSupply●in permitting	Stock		MW		
invest BES	Market	Action	newSupply●maintenance length	Stock		Hour		Only for nuclear. Set in entities. Should be 1.5 months (1095 hours), s.t. utilization factor comes to 10.5/12 = 87.5% (SFOE, 2015).
invest BES	Market	Action	newSupply●maintenance month	Stock		Dmnl		Only for nuclear. Pre-set.
invest BES	Market	Action	newSupply●mothball timer	Stock		Hour		
invest BES	Market	Action	newSupply●outage timer	Stock		Hour		
invest BES	Market	Action	newSupply●price average	Stock	Parent.price average yearly	CHF/(MW*hour)		
invest BES	Market	Action	newSupply●price average m1	Stock	Parent.price average yearly m1	CHF/(MW*hour)		
invest BES	Market	Action	newSupply●price average m2	Stock	Parent.price average yearly m2	CHF/(MW*hour)		
invest BES	Market	Action	newSupply●price average m3	Stock	Parent.price average yearly m3	CHF/(MW*hour)		
invest BES	Market	Action	newSupply●price average winter	Stock		CHF/(MW*Hour)		Average price received for this supply option in the winter months (jan, feb, mar).
invest BES	Market	Action	newSupply●renovated	Stock		Dmnl		Once a plant has been renovated, it counts here. Serves as a limit for renovation.
invest BES	Market	Action	newSupply●reserved amount	Stock		MW*hour		
invest BES	Market	Action	newSupply●reservoir	Stock	0	MW*hour		
invest BES	Market	Action	newSupply●reservoir finite	Stock	1	1		1 = yes, 0 = no
invest BES	Market	Action	newSupply●reservoir initial maximum	Stock	Parent.distance from target BES	MW*hour		
invest BES	Market	Action	newSupply●reservoir yearly degradation	Stock	0.01	1		
invest BES	Market	Action	newSupply●revenues	Stock		CHF		

invest BES	Market	Action	newSupply●storage cost	Stock		CHF/(MW *hour*hour)		Inventory cost for keeping water/fuel on supply. Need to check units
invest BES	Market	Action	newSupply●storage efficiency	Stock	0.95	1		Roundtrip efficiency, because production has no efficiency losses.
invest BES	Market	Action	newSupply●storage enabled	Stock	1	1		1 = yes, 0 = no. Used whether storage demand bid is used or not.
invest BES	Market	Action	newSupply●time construction	Stock		year		
invest BES	Market	Action	newSupply●time maximum life	Stock	20	year		
invest BES	Market	Action	newSupply●time permitting	Stock		year		
invest BES	Market	Action	newSupply●utilization factor	Stock		1		
invest BES	Market	Action	newSupply●volume sold	Stock		MW*hour		
invest BES	Market	Action	newSupply●volume winter	Stock		MW*hour		
invest BES	Market	Action	newSupply●volume yearly	Stock		MW*hour		
invest BES	Market	Action	Invoker	Reference			Target Type: Market	
invest BES	Market	Action	newSupply	Reference	Condition: SupplyID		Target Type: Supply	
invest BES	Market	Action	Parent	Reference			Target Type: Market	
invest BES	Market	Action	trigger create pair	Trigger	true		Action to Invoke: newSupply.create pair, When: OnCondition, Sequence No.: 1	
E_process demand	Market	Action						
E_process demand	Market	Action	supply to be distributed	Stock	Parent.total supplied-Parent.ENS.capacity operating	MW		Removes, if relevant, the amount supplied by the "ENS" plant, i.e., energy not served. This is so that it is also clear who gets cut off from the electricity, based on their bid. Typically, this means the inflexible consumers do not get their whole electricity demand met (the flexible consumers won't pay for electricity in case of VOLL).
E_process demand	Market	Action	Flow2	Flow	refDemand.demand amount	MW	Outflow (supply to be distributed)	Can go negative, not a problem. Counts down.
E_process demand	Market	Action	Invoker	Reference			Target Type: Market	
E_process demand	Market	Action	Parent	Reference			Target Type: Market	
E_process demand	Market	Action	Parent.ENS	Reference	Condition: SupplyID "ENS"		Target Type: Supply	
E_process demand	Market	Action	refDemand	Reference	Condition: DemandID		Target Type: Demand	
D2B_process supply by price	Market	Action						
D2B_process supply by price	Market	Action	available bidding capacity	Auxiliary	IfThenElse(refSupply.country="FR",max(0,min(refSupply.bidding capacity,Parent.import capacity remaining)),refSupply.bidding capacity)	MW	Value	

D2B_process supply by price	Market	Action	supply option count	Stock	Parent.Supply_on.Count	1		
D2B_process supply by price	Market	Action	count down	Flow	1	1	Outflow (supply option count)	
D2B_process supply by price	Market	Action	Invoker	Reference			Target Type: Market	
D2B_process supply by price	Market	Action	Parent	Reference			Target Type: Market	
D2B_process supply by price	Market	Action	Parent.Supply	Reference			Target Type: Supply[]	
D2B_process supply by price	Market	Action	Parent.Supply_on	Reference	Condition: status "on"		Target Type: Supply[status]	
D2B_process supply by price	Market	Action	refSupply	Reference	Condition: SupplyID		Target Type: Supply	
D2B_process supply by price	Market	Action	trigger E	Trigger	supply option count=0		Action to Invoke: Parent.E_process demand, When: OnCondition, Sequence No.: 1	Price found (by demand) and supply turned on. Only need to process demand, last step.
D2A_set price by demand	Market	Action						
D2A_set price by demand	Market	Action	FR	Reference	Condition: SupplyID "FR"		Target Type: Supply	
D2A_set price by demand	Market	Action	Invoker	Reference			Target Type: Market	
D2A_set price by demand	Market	Action	Parent	Reference			Target Type: Market	
D2A_set price by demand	Market	Action	trigger D2B	Trigger	true		Action to Invoke: Parent.D2B_process supply by price, When: OnCondition, Sequence No.: 1	Since we have a new price, we need to process the supply-side again so that only those at this price will supply.
D1_count supply	Market	Action						
D1_count supply	Market	Action	supply option count	Stock	Parent.Supply_on.Count	1		
D1_count supply	Market	Action	count down	Flow	1	1	Outflow (supply option count)	
D1_count supply	Market	Action	Invoker	Reference			Target Type: Market	
D1_count supply	Market	Action	Parent	Reference			Target Type: Market	
D1_count supply	Market	Action	Parent.Supply	Reference			Target Type: Supply[]	
D1_count supply	Market	Action	Parent.Supply_on	Reference	Condition: status "on"		Target Type: Supply[status]	
D1_count supply	Market	Action	refSupply	Reference	Condition: SupplyID		Target Type: Supply	
D1_count supply	Market	Action	trigger E	Trigger	supply option count=0		Action to Invoke: Parent.E_process demand, When: OnCondition, Sequence No.: 1	Go to final step.
C_process supply by demand	Market	Action						
C_process supply by demand	Market	Action	available bidding capacity	Auxiliary	IfThenElse(refSupply.country="FR",max(0,min(refSupply.bidding capacity,Parent.import capacity remaining)),refSupply.bidding capacity)	MW	Value	Takes the bidding capacity, unless it is located in FR, in which case it takes the min between the bidding capacity and the import capacity.

C_process supply by demand	Market	Action	demand to be met	Stock	Invoker.sum demand options	MW		Based on the considered demand options in B.
C_process supply by demand	Market	Action	supply demand	Flow	available bidding capacity	MW	Outflow (demand to be met)	Reduces demand to be met by each supply option's bidding capacity.
C_process supply by demand	Market	Action	supply option count	Stock	Parent.Supply_on.Count	1		Counts how many supply options left to be considered. When it reaches zero (last one), it triggers one of the new actions.
C_process supply by demand	Market	Action	count down	Flow	1	1	Outflow (supply option count)	
C_process supply by demand	Market	Action	Invoker	Reference			Target Type: Market	
C_process supply by demand	Market	Action	Parent	Reference			Target Type: Market	
C_process supply by demand	Market	Action	Parent.Supply	Reference			Target Type: Supply[]	
C_process supply by demand	Market	Action	Parent.Supply_on	Reference	Condition: status "on"		Target Type: Supply[status]	
C_process supply by demand	Market	Action	refSupply	Reference	Condition: SupplyID		Target Type: Supply	
C_process supply by demand	Market	Action	trigger A	Trigger	(Invoker.spot price<=Parent.next demand price) AND (supply option count=0) AND (Parent.finished loop=0)		Action to Invoke: Parent.A_clear market, When: OnCondition, Sequence No.: 1	Recursive. At the end of the countdown, if the next demand price is larger than the currently found spot price, starts the process again at the "clear market" stage. This command action adds 1 to the counter, adds the next batch of demand to the demand amount, then starts the process supply again to find the new price.
C_process supply by demand	Market	Action	trigger D1	Trigger	(Invoker.spot price>Parent.next demand price) AND (supply option count=0) AND (Invoker.spot price<=Parent.last demand price) AND (Parent.finished loop=0)		Action to Invoke: Parent.D1_count supply, When: OnCondition, Sequence No.: 1	At the end, if the spot price is higher than the next demand option (i.e., nobody will demand extra at this price), and the price is lower than or equal to the current demand option (i.e., the last consumer will take their full demand), it will go stop, as the price is found (demand is fixed, the supply is accordingly distributed). Since it stops, it goes to process demand to find out who gets what, but it needs CS first to count the supply to be distributed.
C_process supply by demand	Market	Action	trigger D2A	Trigger	(Invoker.spot price>Parent.next demand price) AND (supply option count=0) AND (Invoker.spot price>Parent.last demand price) AND (Parent.finished loop=0)		Action to Invoke: Parent.D2A_set price by demand, When: OnCondition, Sequence No.: 1	At the end, if the spot price is higher than the next demand option (i.e., nobody will demand extra at this price), and the price is higher than the current demand option (i.e., the last consumer has risen the price and it does not want to do so), it will go to set the price by demand, which will trigger a process supply by price. The price is fixed, and the consumers will only get so much as to not raise the price (the last consumer gets their demand partially).
B_set price by supply	Market	Action						
B_set price by supply	Market	Action	demand option count	Stock	Parent.Demand_on.Count	1		

B_set price by supply	Market	Action	countdown	Flow	1	1	Outflow (demand option count)	
B_set price by supply	Market	Action	Invoker	Reference			Target Type: Market	
B_set price by supply	Market	Action	Parent	Reference			Target Type: Market	
B_set price by supply	Market	Action	Parent.demand	Reference			Target Type: Demand[]	
B_set price by supply	Market	Action	Parent.Demand_on	Reference	Condition: status "on"		Target Type: Demand[status]	
B_set price by supply	Market	Action	refDemand	Reference	Condition: DemandID		Target Type: Demand	
B_set price by supply	Market	Action	trigger C	Trigger	demand option count=0		Action to Invoke: Parent.C_process supply by demand, When: OnCondition, Sequence No.: 1	
A_clear market	Market	Action						
A_clear market	Market	Action	FR	Reference	Condition: SupplyID "FR"		Target Type: Supply	
A_clear market	Market	Action	Invoker	Reference			Target Type: Market	
A_clear market	Market	Action	Parent	Reference			Target Type: Market	
A_clear market	Market	Action	trigger B	Trigger	true		Action to Invoke: Parent.B_set price by supply, When: OnCondition, Sequence No.: 1	
Investor		Entity						
Investor		Entity	InvestorID	Attribute			key	
Investor		Entity	type	Attribute	"gas"			Type of investor.
Investor		Entity	cost investment	Auxiliary	cost investment current*time.MW to kW*time.USD to CHF	CHF/MW	Value	
Investor		Entity	cost investment current	Auxiliary	cost investment lookup(time.year AD)	$/kW	Value	
Investor		Entity	cost marginal	Auxiliary	cost operating variable+plants_owned_type_on.Average fuel cost-IfThenElse(((type="solar") OR (type="wind")),market.production subsidy,0)	CHF/(MW *hour)	Value	Wind/solar get the subsidy, not gas.
Investor		Entity	cost operating fixed	Auxiliary	cost operating fixed current*time.USD to CHF*time.MW to kW	CHF/(MW *Year)	Value	
Investor		Entity	cost operating fixed current	Auxiliary	cost operating fixed lookup(time.year AD)	$/(kW*year)	Value	
Investor		Entity	cost operating variable	Auxiliary	cost operating variable current*time.USD to CHF	CHF/(MW *hour)	Value	
Investor		Entity	cost operating variable current	Auxiliary	cost operating variable lookup(time.year AD)	$/(MW*hour)	Value	
Investor		Entity	discount rate	Auxiliary	0.08	1	Constant Value	Pure investor preference. Risk factor not included (differs per investment type).
Investor		Entity	dispatchable	Auxiliary	if(type="gas") {1} else {0}	1	Value	
Investor		Entity	emissions factor	Auxiliary	plants_all_type.Average emissions factor	1	Value	
Investor		Entity	investment hurdle rate	Auxiliary	0.1	1	Constant Value	Above 0 means a profitable investment. 0.1 means NPV is 10% higher than initial investment.
Investor		Entity	NPV10	Auxiliary	(time.hours per year*(price 5-cost marginal)*utilization factor-cost operating fixed)*(1/(1+WACC)^5+1/(1+WACC)^6+1/(1+WACC)^7+1/(1+WACC)^8 +1/(1+WACC)^9+1/(1+WACC)^10)	CHF	Value	

Investor		Entity	NPV15	Auxiliary	(time.hours per year*(price 5-cost marginal)*utilization factor-cost operating fixed)*(1/(1+WACC)^11+1/(1+WACC)^12+1/(1+WACC)^13+1/(1+WACC)^14+1/(1+WACC)^15)	CHF	Value	
Investor		Entity	NPV20	Auxiliary	(time.hours per year*(price 5-cost marginal)*utilization factor-cost operating fixed)*(1/(1+WACC)^16+1/(1+WACC)^17+1/(1+WACC)^18+1/(1+WACC)^19+1/(1+WACC)^20)	CHF	Value	
Investor		Entity	NPV5	Auxiliary	-cost investment +(time.hours per year*(price 1-cost marginal)*utilization factor-cost operating fixed)/(1+WACC)^1 +(time.hours per year*(price 2-cost marginal)*utilization factor-cost operating fixed)/(1+WACC)^2 +(time.hours per year*(price 3-cost marginal)*utilization factor-cost operating fixed)/(1+WACC)^3 +(time.hours per year*(price 4-cost marginal)*utilization factor-cost operating fixed)/(1+WACC)^4	CHF	Value	
Investor		Entity	plant lifetime	Auxiliary	20	year	Value	
Investor		Entity	plant net present value	Auxiliary	investment size*(NPV5+NPV10+NPV15+NPV20)	CHF	Value	
Investor		Entity	plant profitability index	Auxiliary	plant net present value/(cost investment*investment size)	1	Value	
Investor		Entity	price 1	Auxiliary	plants_owned_type_on.price trend slope*(time.year AD+1)+plants_owned_type_on.price trend constant	CHF/(MW*hour)	Value	
Investor		Entity	price 2	Auxiliary	plants_owned_type_on.price trend slope*(time.year AD+2)+plants_owned_type_on.price trend constant	CHF/(MW*hour)	Value	
Investor		Entity	price 3	Auxiliary	plants_owned_type_on.price trend slope*(time.year AD+3)+plants_owned_type_on.price trend constant	CHF/(MW*hour)	Value	
Investor		Entity	price 4	Auxiliary	plants_owned_type_on.price trend slope*(time.year AD+4)+plants_owned_type_on.price trend constant	CHF/(MW*hour)	Value	
Investor		Entity	price 5	Auxiliary	plants_owned_type_on.price trend slope*(time.year AD+5)+plants_owned_type_on.price trend constant	CHF/(MW*hour)	Value	The expected price in 5 years for this investors type, based on the forecasted growth rate.
Investor		Entity	reference price	Auxiliary	3*(market.price average yearly+market.price average yearly m1+market.price average yearly m2)/3	CHF/(MW*hour)	Value	This is the price they use for calculating opportunity costs of their (finite, storage) power plants (battery, hydro, waste). Should depend on the historic market. Average selling price (if selling entire reservoir perfectly for the reference price) would be half of this value. Takes weighted average price of the last 3 years, times two.
Investor		Entity	renovation hurdle rate	Auxiliary	0	1	Value	
Investor		Entity	risk rate	Auxiliary	0.01	1	Constant Value	Differs per plant type / investor.
Investor		Entity	storage cost	Auxiliary	plants_all_type.Average storage cost	CHF/(MW*hour*hour)	Value	
Investor		Entity	time construction	Auxiliary	1	year	Constant Value	
Investor		Entity	time lifetime maximum	Auxiliary	20	year	Constant Value	
Investor		Entity	time permitting	Auxiliary	1	year	Constant Value	
Investor		Entity	utilization factor	Auxiliary	max(0.1,IfThenElse(type="gas",plants_owned_type.Average utilization factor*(plants_all.Sum derated capacity 3/(plants_all.Sum derated capacity 3+investment size*plants_owned_type.Average utilization	1	Value	Utilization factor of the projected plant. To use in profitability analysis.

					factor)),IfThenElse(type="solar",solar weather.potential multiplication factor,wind weather.potential multiplication factor)))			Flexible load will have less occasion to run if there is more installed capacity. Approximated based on de-rated capacity 3 years ahead (building takes at least that long, do not have more foresight). Does not work for wind/solar because they always run when possible; based on weather rather than observed values.
Investor		Entity	WACC	Auxiliary	discount rate+risk rate	1	Value	
Investor		Entity	cost investment lookup	TableFunction	0,2051,-1,1,2015,1,2050,1	year		From NREL (2018). Low scenario
Investor		Entity	cost operating fixed lookup	TableFunction	0,2051,-1,1,2015,1,2050,1	year		From NREL (2018). Low scenario
Investor		Entity	cost operating variable lookup	TableFunction	0,2051,-1,1,2015,1,2050,1	Year		From NREL (2018). Low scenario
Investor		Entity	investment size	Stock	100	MW		Depends on the type of investor (gas, wind, solar).
Investor		Entity	market	Reference			Target Type: Market	
Investor		Entity	Model	Reference			Target Type: Model	
Investor		Entity	plants_all	Reference			Target Type: Supply[]	
Investor		Entity	plants_all_type	Reference	Condition: type type		Target Type: Supply[type]	
Investor		Entity	plants_owned_type	Reference	Condition: investor InvestorID, Condition: type type		Target Type: Supply[investor,type]	
Investor		Entity	plants_owned_type_on	Reference	Condition: investor InvestorID, Condition: status "on", Condition: type type		Target Type: Supply[investor,status,type]	
Investor		Entity	solar	Reference	Condition: investor InvestorID, Condition: type "solar"		Target Type: Supply[investor,type]	
Investor		Entity	solar weather	Reference	Condition: WeatherID "solar"		Target Type: Weather	
Investor		Entity	time	Reference			Target Type: Time	
Investor		Entity	weather	Reference	Condition: WeatherID "none"		Target Type: Weather	
Investor		Entity	wind	Reference	Condition: investor InvestorID, Condition: type "wind"		Target Type: Supply[investor,type]	
Investor		Entity	wind weather	Reference	Condition: WeatherID "wind"		Target Type: Weather	
Investor		Entity	trigger invest	Trigger	(plant profitability index>investment hurdle rate) AND (time.allow investments=1) AND (time.end of month=1) AND (((type="wind") AND (plants_all_type.sum all capacity<weather.wind maximum potential)) OR ((type="solar") AND (plants_all_type.sum all capacity<weather.solar maximum potential)) OR (type="gas"))		Action to Invoke: A_check permits, When: PeriodStart, Sequence No.: 1	
B1_invest	Investor	Action						
B1_invest	Investor	Action	newSupply●country	Attribute	"CH"			Four options: "CH", "IT", "FR", "DE". Used for import price calculation (import is modeled as a supply option), as well as import contracts (multiple entities in a single country compete for import capacity).
B1_invest	Investor	Action	newSupply●demand link	Attribute	"domestic"			Links to demand used for country/storage plants. Links to Demand|0 as standard, should not be used if not the corresponding type.

B1_invest	Investor	Action	newSupply●investor	Attribute	Parent.InvestorID			
B1_invest	Investor	Action	newSupply●status	Attribute	"Off"			
B1_invest	Investor	Action	newSupply●SupplyID	Attribute	Parent.type+"_"+time.year AD		key	
B1_invest	Investor	Action	newSupply●type	Attribute	Parent.type			"gas", "wind", "nuclear", "solar", "hydro", "ROR","trade", "contract", "ENS".
B1_invest	Investor	Action	newSupply●weather	Attribute	if(Parent.type="gas") {"none"} else {Parent.type}			
B1_invest	Investor	Action	newSupply●age	Stock	0	year		
B1_invest	Investor	Action	newSupply●approved permits	Stock	0	MW		
B1_invest	Investor	Action	newSupply●capacity in construction	Stock	0	MW		
B1_invest	Investor	Action	newSupply●capacity installed	Stock	0	MW		
B1_invest	Investor	Action	newSupply●capacity installed 1	Stock	0	MW		
B1_invest	Investor	Action	newSupply●capacity installed 2	Stock	0	MW		
B1_invest	Investor	Action	newSupply●capacity installed 3	Stock	0	MW		
B1_invest	Investor	Action	newSupply●capacity mothballed	Stock	0	MW		
B1_invest	Investor	Action	newSupply●capacity operating	Stock	0	MW		
B1_invest	Investor	Action	newSupply●cost investment	Stock	Parent.cost investment current	$/kW		Retains information, used for renovation purposes.
B1_invest	Investor	Action	newSupply●cost operating fixed	Stock	Parent.cost operating fixed current	$/(kW*year)		
B1_invest	Investor	Action	newSupply●cost operating variable	Stock	Parent.cost operating variable current	$/(MW*hour)		
B1_invest	Investor	Action	newSupply●derating factor	Stock	Parent.utilization factor	1		Need to set during initialization. Used for security margin calculations. In the case of trade, calculate historically by looking at whether you import or export during peak hours.
B1_invest	Investor	Action	newSupply●dispatchable	Stock	Parent.dispatchable	1		1=yes, 0=no. Whether the unit can actually be controlled, used for participation in reserve.
B1_invest	Investor	Action	newSupply●emissions factor	Stock	Parent.emissions factor	TC/(MW*hour)		TC = ton of carbon.
B1_invest	Investor	Action	newSupply●forced outage rate	Stock		Dmnl		
B1_invest	Investor	Action	newSupply●in maintenance	Stock		Hour		
B1_invest	Investor	Action	newSupply●in permitting	Stock	Parent.investment size	MW		
B1_invest	Investor	Action	newSupply●maintenance length	Stock		Hour		

B1_invest	Investor	Action	newSupply●maintenance month	Stock		Dmnl		
B1_invest	Investor	Action	newSupply●mothball timer	Stock		Hour		
B1_invest	Investor	Action	newSupply●outage timer	Stock		Hour		
B1_invest	Investor	Action	newSupply●price average	Stock	Parent.price 1	CHF/(MW *hour)		
B1_invest	Investor	Action	newSupply●price average m1	Stock	Parent.price 1	CHF/(MW *hour)		
B1_invest	Investor	Action	newSupply●price average m2	Stock	Parent.price 1	CHF/(MW *hour)		
B1_invest	Investor	Action	newSupply●price average m3	Stock	Parent.price 1	CHF/(MW *hour)		
B1_invest	Investor	Action	newSupply●price average winter	Stock		CHF/(MW *Hour)		
B1_invest	Investor	Action	newSupply●renovated	Stock		Dmnl		
B1_invest	Investor	Action	newSupply●reserved amount	Stock		MW*hour		
B1_invest	Investor	Action	newSupply●reservoir	Stock	0	MW*hour		
B1_invest	Investor	Action	newSupply●reservoir finite	Stock	0	1		1 = yes, 0 = no
B1_invest	Investor	Action	newSupply●reservoir initial maximum	Stock	0	MW*hour		
B1_invest	Investor	Action	newSupply●reservoir yearly degradation	Stock	0	1		
B1_invest	Investor	Action	newSupply●revenues	Stock	0	CHF		
B1_invest	Investor	Action	newSupply●storage cost	Stock	Parent.storage cost	CHF/(MW *hour*hour)		Inventory cost for keeping water/fuel on supply. Need to check units
B1_invest	Investor	Action	newSupply●storage efficiency	Stock	1	1		Roundtrip efficiency, because production has no efficiency losses.
B1_invest	Investor	Action	newSupply●storage enabled	Stock	0	1		1 = yes, 0 = no
B1_invest	Investor	Action	newSupply●time construction	Stock	Parent.time construction	year		
B1_invest	Investor	Action	newSupply●time maximum life	Stock	Parent.time lifetime maximum	year		
B1_invest	Investor	Action	newSupply●time permitting	Stock	Parent.time permitting	year		
B1_invest	Investor	Action	newSupply●utilization factor	Stock	Parent.utilization factor	1		
B1_invest	Investor	Action	newSupply●volume sold	Stock	0	MW*hour		
B1_invest	Investor	Action	newSupply●volume winter	Stock		MW*hour		
B1_invest	Investor	Action	newSupply●volume yearly	Stock	0	MW*hour		

B1_invest	Investor	Action	Invoker	Reference	Condition: InvestorID		Target Type: Investor	
B1_invest	Investor	Action	newSupply	Reference	Condition: SupplyID		Target Type: Supply	
B1_invest	Investor	Action	Parent	Reference	Condition: InvestorID		Target Type: Investor	
B1_invest	Investor	Action	time	Reference			Target Type: Time	
B_check limit	Investor	Action						
B_check limit	Investor	Action	Invoker	Reference	Condition: InvestorID		Target Type: Investor	
B_check limit	Investor	Action	market	Reference			Target Type: Market	
B_check limit	Investor	Action	Parent	Reference	Condition: InvestorID		Target Type: Investor	
B_check limit	Investor	Action	trigger B1	Trigger	countdown>0		Action to Invoke: Parent.B1_invest, When: OnCondition, Sequence No.: 1	
A1_choose project	Investor	Action						
A1_choose project	Investor	Action	Count	Stock	1	dmnl		
A1_choose project	Investor	Action	countdown	Flow	1	Dmnl	Outflow (Count)	
A1_choose project	Investor	Action	Invoker	Reference	Condition: InvestorID		Target Type: Investor	
A1_choose project	Investor	Action	Parent	Reference	Condition: InvestorID		Target Type: Investor	
A1_choose project	Investor	Action	refSupply	Reference	Condition: SupplyID		Target Type: Supply	
A1_choose project	Investor	Action	trigger grant permit	Trigger	true		Action to Invoke: refSupply.construction start, When: OnCondition, Sequence No.: 1	
A_check permits	Investor	Action						
A_check permits	Investor	Action	Invoker	Reference	Condition: InvestorID		Target Type: Investor	
A_check permits	Investor	Action	Parent	Reference	Condition: InvestorID		Target Type: Investor	
A_check permits	Investor	Action	Parent.plants_owned_type	Reference	Condition: investor Parent.InvestorID, Condition: type Parent.type		Target Type: Supply[investor,type]	
A_check permits	Investor	Action	trigger A1	Trigger	Parent.plants_owned_type.Sum approved permits>0		Action to Invoke: Parent.A1_choose project, When: OnCondition, Sequence No.: 1	
A_check permits	Investor	Action	trigger B	Trigger	Parent.plants_owned_type.Sum approved permits=0		Action to Invoke: Parent.B_check limit, When: OnCondition, Sequence No.: 1	
Investor[]	Investor	Collection						
Investor[]	Investor	Collection	Count	Auxiliary		dmnl	Value	Built-in variable. Reports the number of entities of this type existing at the end of each time slice.
Demand		Entity						
Demand		Entity	country	Attribute	"CH"			Four options: "CH", "IT", "FR", "DE".
Demand		Entity	DemandID	Attribute			key	
Demand		Entity	status	Attribute	"on"			On or off.
Demand		Entity	supply link	Attribute	"ENS"			Links to a supply entity, can either be a country or power plant. Uses ENS for

								basic case, but should not be used if it is not really a power plant.
Demand		Entity	type	Attribute	"DR"			So far: "domestic", "trade", or "storage", "DR", or "interrupt".
Demand		Entity	amount stored	Auxiliary	IfThenElse(Plant.reservoir finite=1,demand met,0)	MW	Value	Has to link back to the power plant. Efficiency is taken care of at the supply entity, so this still gets reduced.
Demand		Entity	annual demand	Auxiliary	IfThenElse(Time.demand scenario=1,demand scenario 1(Time.year AD),IfThenElse(Time.demand scenario=2,demand scenario 2(Time.year AD),IfThenElse(time.demand scenario=3,demand scenario 3(Time.year AD),demand scenario 4)))	MW*hour	Value	
Demand		Entity	bidding capacity consumption	Auxiliary	consumptive demand-bidding capacity interruptible contracts-DR.Sum demand base	CHF/(MW *Hour)	Value	Takes the consumptive demand, and takes out all flexible loads (i.e. contracts and DR) so that these only get met when the price is lower than their level.
Demand		Entity	bidding capacity DR	Auxiliary	min(demand base+curtailed demand,demand base*1.5)	MW	Value	Basically, the base demand is asked, unless some curtailed energy needs to be recovered, in which case that is also asked (at the same price). This is capped at 1.5 as an estimate of maximum scale-up.
Demand		Entity	bidding capacity interruptible contracts	Auxiliary	0.05*peak demand	MW	Value	Interruptible contracts
Demand		Entity	bidding capacity storage	Auxiliary	min(ZIDZ(room left,plant.storage efficiency),Plant.capacity fixed)*Plant.storage enabled* IfThenElse(plant.reservoir<plant.reserved amount,0,1)	MW	Value	Minimum either fixed capacity or the remaining reservoir increased by efficiency, maximum that and 0 (ie always positive). If "storage enabled" = 0, there is no bid, and if the reserve is activated, i.e. there is less water than there is reserved, there is also no bid.
Demand		Entity	bidding price storage	Auxiliary	Plant.opportunity cost storage*Plant.storage enabled	CHF/MWh	Value	If "storage enabled" = 0, there is no bid. Otherwise, use the opportunity cost.
Demand		Entity	consumptive demand	Auxiliary	((IfThenElse(Time.demand scenario=1,demand scenario 1(Time.year AD),IfThenElse(Time.demand scenario=2,demand scenario 2(Time.year AD),IfThenElse(time.demand scenario=3,demand scenario 3(Time.year AD),demand scenario 4))) * IfThenElse(Time.profile year=15,demand profile 15(Time.hour of year),IfThenElse(Time.profile year=16,demand profile 16(Time.hour of year),demand profile 17(Time.hour of year)))))	MW	Value	
Demand		Entity	demand amount	Auxiliary	max(0,(IfThenElse(type="trade",export capacity,IfThenElse(type="storage",bidding capacity storage,IfThenElse(type="domestic",bidding capacity consumption,IfThenElse(type="interrupt", bidding capacity interruptible contracts,bidding capacity DR))))))	MW	Value	Takes the DR capacity (base plus maybe curtailed energy) unless it is an interruptible contract (which depends on peak demand), trade, storage or consumer demand entity.
Demand		Entity	demand price	Auxiliary	IfThenElse(type="trade",export price,IfThenElse(type="storage",bidding price storage,IfThenElse(type="domestic",market.VOLL, demand base price)))	CHF/(MW *Hour)	Value	Takes the base price (set in initialization) unless it is a trade, storage or consumer demand entity (i.e. for contracts and DR).
Demand		Entity	demand scenario 4	Auxiliary	demand scenario 3(Time.start year)*(1+Time.demand growth percentage/100)^(Time.year AD-Time.start year)	MW*hour /year	Value	Growing by the percentage each year. Different from the others, which are gov based.
Demand		Entity	export capacity	Auxiliary	IfThenElse(Time.profile year=15,export NTC multiplier 15(Time.hour of year),IfThenElse(Time.profile year=16,export NTC multiplier 16(Time.hour of year),export NTC multiplier 17(Time.hour of year))) *	MW	Value	

					IfThenElse(Time.NTC scenario=1,export NTC scenario 1(Time.year AD),export NTC scenario 2(Time.year AD)) *Time.NTC limit factor			
Demand		Entity	export price	Auxiliary	(IfThenElse(Time.profile year=15,foreign price 15(Time.hour of year),IfThenElse(Time.profile year=16,foreign price 16(Time.hour of year),foreign price 17(Time.hour of year))) * IfThenElse(Time.foreign price scenario=1,foreign price scenario 1(Time.year AD),IfThenElse(Time.foreign price scenario=2,foreign price scenario 2(Time.year AD),IfThenElse(Time.foreign price scenario=3,foreign price scenario 3(Time.year AD),IfThenElse(Time.foreign price scenario=4,foreign price scenario 4(Time.year AD),IfThenElse(Time.foreign price scenario=0,foreign price scenario 0(Time.year AD),0))))))*Time.EUR to CHF	CHF/(MW *hour)	Value	Resorts to 0 if the Time.foreign price scenario variable is not 0-4.
Demand		Entity	export price smoothed	Auxiliary	SMOOTHI(export price,336,50)	CHF/(MW *hour)	Value	
Demand		Entity	export price smoothed SMOOTHI1 DelayTime	Auxiliary	336		Value	
Demand		Entity	export price smoothed SMOOTHI1 InitialValue	Auxiliary	50		Value	
Demand		Entity	export price smoothed SMOOTHI1 Input	Auxiliary	export price		Value	
Demand		Entity	peak demand	Auxiliary	IfThenElse(time.demand scenario=1,demand scenario 1(time.year AD),IfThenElse(time.demand scenario=2,demand scenario 2(time.year AD),IfThenElse(time.demand scenario=3,demand scenario 3(time.year AD),IfThenElse(time.demand scenario=4, demand scenario 4,10000))))*peak percentage	MW	Value	IfThenElse(Time.demand scenario=1,demand scenario 1(Time.year AD),IfThenElse(Time.demand scenario=2,demand scenario 2(Time.year AD),IfThenElse(Time.Time.demand scenario=3,demand scenario 3(Time.year AD),demand scenario 4)))*peak percentage
Demand		Entity	peak percentage	Auxiliary	0.00015752	1	Constant Value	5 year average (2010-2014) of the highest 365 (=1/24th of the time) demand. Multiply by yearly consumption to find peak in MW.
Demand		Entity	room left	Auxiliary	max(0,Plant.reservoir maximum-Plant.reservoir)	MW*Hour	Value	
Demand		Entity	transmission losses	Auxiliary	0.07	1	Value	
Demand		Entity	volume yearly real consumption	Auxiliary	IfThenElse((type="DR") OR (type="domestic") OR (type="interrupt"), volume yearly, 0)	MW*Hour	Value	Actual domestic consumption, excluding export and storage needs.
Demand		Entity	demand profile 15	TableFunction	0,8761,0,2,0,0.000114155251,8760,0.000114155251	hour		
Demand		Entity	demand profile 16	TableFunction	-1,8761,0,2,0,0.000114155251,8760,0.000114155251	hour		
Demand		Entity	demand profile 17	TableFunction	-1,8761,0,8761,0,0.000114155251,8760,0.000114155251	hour		
Demand		Entity	demand scenario 1	TableFunction	2010,2050,50000000,60600001,2017,58483000,2022,57300000,2027,56200000,2032,55500000,2037,55100000	year		BFE 2018 system adequacy study. NEP scenario (lowest). 2017 is from electricity statistics.
Demand		Entity	demand scenario 2	TableFunction	2010,2051,-1,60300001,2017,58483000,2022,58300000,2027,58600000,2032,59200000,2037,60300000	year		BFE 2018 system adequacy study. POM scenario (mid). 2018 is from electricity statistics 2017.
Demand		Entity	demand scenario 3	TableFunction	2010,2051,50000000,64300001,2017,58483000,2022,60100000,2027,61300000,2032,62700000,2037,64300000	year		BFE 2018 system adequacy study. WWB scenario (highest).2017 value is from energy statistics (2018)

Demand		Entity	export NTC multiplier 15	TableFunction	0,8761,0,2,0,1,8760,1	hour		
Demand		Entity	export NTC multiplier 16	TableFunction	0,8761,0,2,0,1,8760,1	hour		
Demand		Entity	export NTC multiplier 17	TableFunction	-1,8761,0,2,0,1,8760,1	hour		
Demand		Entity	export NTC scenario 1	TableFunction	0,2051,0,101,2015,0,2050,0	year		
Demand		Entity	export NTC scenario 2	TableFunction	0,2051,0,51,2015,0,2050,0	year		
Demand		Entity	foreign price 15	TableFunction	-1,8761,0,2,0,1,8760,1	hour		
Demand		Entity	foreign price 16	TableFunction	-1,8761,0,2,0,1,8760,1	hour		
Demand		Entity	foreign price 17	TableFunction	-1,8761,0,11,0,1,8760,1	hour		
Demand		Entity	foreign price scenario 0	TableFunction	0,2051,-1,1,2015,0,2050,0	year		Very low (-3%).
Demand		Entity	foreign price scenario 1	TableFunction	0,2051,0,51,2015,0,2050,0	year		
Demand		Entity	foreign price scenario 2	TableFunction	0,2051,0,51,2015,0,2050,0	year		
Demand		Entity	foreign price scenario 3	TableFunction	0,2051,0,51,2015,50,2050,50	Hour		
Demand		Entity	foreign price scenario 4	TableFunction	0,2051,-1,1,2015,0,2050,0	year		Very high; 3%
Demand		Entity	curtailed demand	Stock	0	MW*hour		The amount of deficiency of energy.
Demand		Entity	curtailment	Flow	IfThenElse(type="DR",max(0,demand base-demand met),0)	MW	Inflow (curtailed demand)	If receiving less than demanded, some energy is curtailed.
Demand		Entity	surplus	Flow	IfThenElse(type="DR",max(0,demand met-demand base),0)	MW	Outflow (curtailed demand)	If producing over the base required, then the surplus is reduced.
Demand		Entity	demand base	Stock	0	MW		For DR.
Demand		Entity	demand base price	Stock	0	CHF/(MW *hour)		For DR.
Demand		Entity	demand met	Stock	0	MW		
Demand		Entity	export price smoothed SMOOTHI1 SMOOTHI	Stock	export price smoothed SMOOTHI1 InitialValue			
Demand		Entity	export price smoothed SMOOTHI1 FlowIn	Flow	(export price smoothed SMOOTHI1 Input - export price smoothed SMOOTHI1 SMOOTHI)/export price smoothed SMOOTHI1 DelayTime		Inflow (export price smoothed SMOOTHI1 SMOOTHI)	
Demand		Entity	price average yearly	Stock	0	CHF/(MW *hour)		
Demand		Entity	revenues	Stock	0	CHF		
Demand		Entity	accumulate revenues	Flow	market.spot price*demand met	CHF/hour	Inflow (revenues)	
Demand		Entity	volume winter	Stock	0	MW*hour		Set by action. Volume of demand received (i.e. consumed) Jan-Mar.
Demand		Entity	volume yearly	Stock	0	MW*hour		
Demand		Entity	volumes	Stock	0	MW*hour		
Demand		Entity	accumulate volumes	Flow	demand met	MW	Inflow (volumes)	
Demand		Entity	DR	Reference	Condition: type "DR"		Target Type: Demand[type]	
Demand		Entity	market	Reference			Target Type: Market	

Demand		Entity	Model	Reference				Target Type: Model	
Demand		Entity	Plant	Reference	Condition: SupplyID supply link			Target Type: Supply	
Demand		Entity	Time	Reference				Target Type: Time	
Demand		Entity	trigger update prices	Trigger	time.hour of year=8759			Action to Invoke: update prices, When: PeriodStart, Sequence No.: 1	
Demand		Entity	trigger update winter	Trigger	time.hour of year=2159			Action to Invoke: update winter, When: PeriodStart, Sequence No.: 1	
update winter	Demand	Action							
update winter	Demand	Action	Invoker	Reference	Condition: DemandID			Target Type: Demand	
update winter	Demand	Action	Parent	Reference	Condition: DemandID			Target Type: Demand	
update prices	Demand	Action							
update prices	Demand	Action	Invoker	Reference	Condition: DemandID			Target Type: Demand	
update prices	Demand	Action	Parent	Reference	Condition: DemandID			Target Type: Demand	
decommission	Demand	Action							
decommission	Demand	Action	Invoker	Reference	Condition: DemandID			Target Type: Demand	
decommission	Demand	Action	Parent	Reference	Condition: DemandID			Target Type: Demand	
Demand[type]	Demand	Collection							
Demand[type]	Demand	Collection	type	Attribute				key	
Demand[type]	Demand	Collection	Count	Auxiliary			dmnl	Value	Built-in variable. Reports the number of entities of this type existing at the end of each time slice.
Demand[type]	Demand	Collection	Sum demand base	Aggregate	Sum		MW	Target Variable: demand base	
Demand[type]	Demand	Collection	Sum volume yearly	Aggregate	Sum		MW*hour	Target Variable: volume yearly	
Demand[status]	Demand	Collection							
Demand[status]	Demand	Collection	status	Attribute				key	
Demand[status]	Demand	Collection	Count	Auxiliary			dmnl	Value	Built-in variable. Reports the number of entities of this type existing at the end of each time slice.
Demand[country]	Demand	Collection							
Demand[country]	Demand	Collection	country	Attribute				key	
Demand[country]	Demand	Collection	Count	Auxiliary			dmnl	Value	Built-in variable. Reports the number of entities of this type existing at the end of each time slice.
Demand[country]	Demand	Collection	Sum volume winter	Aggregate	Sum		MW*hour	Target Variable: volume winter	
Demand[country]	Demand	Collection	Sum volume yearly	Aggregate	Sum		MW*hour	Target Variable: volume yearly	
Demand[country]	Demand	Collection	Sum volume yearly real consumption	Aggregate	Sum		MW*Hour	Target Variable: volume yearly real consumption	
Demand[]	Demand	Collection							

Demand[]	Demand	Collection	Count	Auxiliary		dmnl	Value	Built-in variable. Reports the number of entities of this type existing at the end of each time slice.
Demand[]	Demand	Collection	Sum demand amount	Aggregate	Sum	MW	Target Variable: demand amount	
Demand[]	Demand	Collection	Sum demand met	Aggregate	Sum	MW	Target Variable: demand met	

Curriculum Vitae

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Education

Ph.D. Management of Technology

École Polytechnique Fédérale de Lausanne (EPFL), Switzerland 09.2016 – 09.2019

Thesis: Policy analysis during socio-technical energy transitions: three essays on the Swiss electricity sector

M.Sc. Energy Management and Sustainability

École Polytechnique Fédérale de Lausanne (EPFL), Switzerland 09.2014 – 08.2016

Thesis: Business implications of the energy transition in Switzerland: making the case for system dynamics as decision support tool

B.Sc. Liberal Arts and Sciences

Amsterdam University College (AUC), Netherlands 09.2012 – 06.2014

University College Roosevelt (UCR), Netherlands 09.2011 – 08.2012

Thesis: European shale gas: evaluating the prospects for shale gas exploitation in Europe based on US experiences

Majors: Physics, Earth Sciences

Minor: Environmental Economics

VWO Gymnasium Natuur en Techniek (*Dutch secondary education*)

Theresialyceum Tilburg, Netherlands 09.2004 – 06.2010

Subjects: Mathematics, Physics, Chemistry, Biology, Dutch, English, Latin, and Civics

Professional experience

Research Assistant, Senior Management 10.2016 – 09.2019

Services Industriels de Genève (SIG), Switzerland

Intern, Senior Strategy Consultant 02.2016 – 08.2016

BKW Energie AG, Switzerland

Environmental Engineer Intern, Public Works and Services Department 07.2015 – 09.2015

Government of Ras al Khaimah (RAK), United Arab Emirates

Laboratory Assistant, Department of Sedimentology 01.2014 – 02.2014

Free University of Amsterdam (VU), Netherlands

Smartphone Crew, Customer Services 10.2012 – 07.2014

Vodafone Retail, Netherlands

Research

Publications (peer reviewed)

van Baal, P. A. (2019). The effectiveness of a strategic energy reserve during the energy transition: the case of Switzerland. *Competition and Regulation in Network Industries, XX*(X), 1-26.

van Baal, P. A. (2019). Analyzing the impact of a strategic energy reserve in Switzerland using agent-based system dynamics modeling. *Conference Proceedings of the Energy for Sustainability International Conference,* July 24-26, Turin, Italy.

van Baal, P. A., & Finger, M. (2019). The effect of European integration on Swiss energy policy and governance. *Politics and Governance, 7*(1), 6-16.

Verhoog, R., van Baal, P., & Finger, M. (2018). System Dynamics Simulation to Explore the Impact of Low European Electricity Prices on Swiss Generation Capacity Investments. In A. B. Dorsman, V. Ş. Ediger, & M. B. Karan (Eds.), *Energy Economy, Finance and Geostrategy* (pp. 31–61). Cham, Switzerland: Springer International Publishing.

van Baal, P., Verhoog, R., & Finger, M. (2017). Not if, but when? Simulating the impact of timing the nuclear phase-out in Switzerland. *Conference Proceedings of the International Symposium for Next Generation Infrastructure*, September 11-13, 2017, London.

van Baal, P. A. (2014). An assessment of fugitive methane emissions emanating from shale gas rigs. *AUC Undergraduate Journal of Liberal Arts & Sciences, Open Issue, 4*(1), 24-29.

Publications (not peer-reviewed)

van Baal, P. A., Finger, M., Maggetti, M., Morger, L., Pflieger, G., & Refle, J. E. (*forthcoming*). *The Swiss energy transition and the relationship with Europe*. National Research Programme 70/71. Bern, Switzerland: Swiss National Science Foundation.

van Baal, P. A., & Finger, M. (2019). L'accord bilatéral sur l'électricité avec l'UE : perspectives sur l'historique et l'avenir d'un accord critique et complexe. *Bulletin, 9*(1).

Academic presentations [selection]

van Baal, P. A. (2019). *Analyzing the impact of a strategic energy reserve in Switzerland using agent-based system dynamics modeling*. 4th Energy for Sustainability International Conference, 2019, July 24-26, Politecnico di Torino, Turin, Italy.

van Baal, P. A. (2018). *Strategic reserves as regime resistance to the Swiss energy transition: a hybrid agent-based system dynamics approach.* 9th International Sustainability Transitions Conference, 2018, 12-14 June, University of Manchester, Manchester, United Kingdom.

van Baal, P. A. (2018). *Capacity remuneration mechanisms as politically articulated regime resistance to the renewable energy transition in Europe.* 3rd Conference of the Network of ECRs in Sustainability Transitions, 2018, 13-15 March, Utrecht University, Utrecht, Netherlands.

van Baal, P.A. (2017). *Not if, but when? Simulating the impact of timing the nuclear phase-out in Switzerland.* 5th International Symposium for Next Generation Infrastructure, 2017, 11-13 September, One Great George Street, London, United Kingdom.

van Baal, P.A. (2017). *Theory and frameworks in sustainability transitions: the benefits and necessity of models and simulation*. 2nd PhDs in Transitions Conference 2017, 27-28 April, EPFL, Lausanne, Switzerland.

van Baal, P.A. (2016). *Simulating Swiss energy transition governance*. 3rd SCCER CREST Conference on Innovations for the Energy Transition 2016, 1 September, ZHAW, Winterthur, Switzerland.

Theses and dissertations

van Baal, P. A. (2019). *Policy analysis during socio-technical energy transitions: three essays on the Swiss electricity sector* (Doctoral dissertation). École Polytechnique Fédérale de Lausanne.

van Baal, P. A. (2016). *Business implications of the Swiss energy transition: making the case for system dynamics as a decision support tool* (Master thesis). École Polytechnique Fédérale de Lausanne.

Van Baal, P. (2014). *European shale gas: evaluating the prospects for shale gas exploitation in Europe based on US experiences* (Bachelor thesis). Amsterdam University College.

Grants and fellowships

Co-recipient (96’000 CHF), principal investigator: Matthias Finger 2018-2019
Project: “Integration of the Swiss energy system into the European energy policy”
Swiss National Science Foundation (SNFS), NRP 70/71 complementary study.

Main recipient (32’000 CHF) 2014-2016
EPFL MES Excellence Fellowship.
École Polytechnique Fédérale de Lausanne.

Networks, nonprofits, and associations

Volunteer, SOS-EAU Giteranyi	2018 – present
Organizer, Network of Early Career Researchers in Sustainability Transitions (NEST)	2017 – present
Event manager, Energy Business, Policy & Technology Group, EPFL	2015
Junior consultant, ShARE Student Think-Tank, EPFL	2014 – 2015
Co-founder, financial officer, TEDxAUCollege, AUC	2013 – 2014
Treasurer, SportsCo, student sports association, UCR	2011 – 2012
Treasurer, Graduation committee, Theresialyceum	2010
President, member, SIAM, student events association, Theresialyceum	2006 – 2010

Languages

English:	C2+
Dutch:	C2+
French:	C1
German:	B1/B2
Spanish:	B1

Honors and awards

Student Excellence Award, École Polytechnique Fédérale de Lausanne (EPFL)	2016
Summa cum laude distinction, Amsterdam University College (AUC)	2014
Cum laude distinction, Theresialyceum Tilburg	2010