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The Energy Departments

Documentation on the Development of the

Swiss TIMES Electricity Model (STEM-E)

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1. Background

Energy is becoming an increasingly important strategic research focus for many governments, to support policy efforts promoting sustainable development [55]. Especially the concept of Sustainable Development requires a long-term perspective. Therefore governments and parliaments in many countries are looking for new approaches to deal with these issues [20]. Analytical tools such as energy models have emerged as a useful methodology for energy research aimed at evaluating future energy supply options and generating insights into some of the associated uncertainties. Importantly, there are many types of energy model covering a wide range of analytical approaches, with tools often developed for specific objectives, with a predefined methodological scope and limited application. In Switzerland, a range of energy models, like energy-economy equilibrium models [5][6][2], technology-rich MARKAL energy system models [48][18] and sector specific energy models [32][12][54] have been implemented for analysing energy and climate mitigation policies. Some of the models are rich in the level of technological detail, while others have a greater focus on the representation of energy-economic linkages. The objectives and scope of these models (Figure 1) are diverse, with different strengths and weakness, providing complementary insights on a range of aspects of the energy system [10].

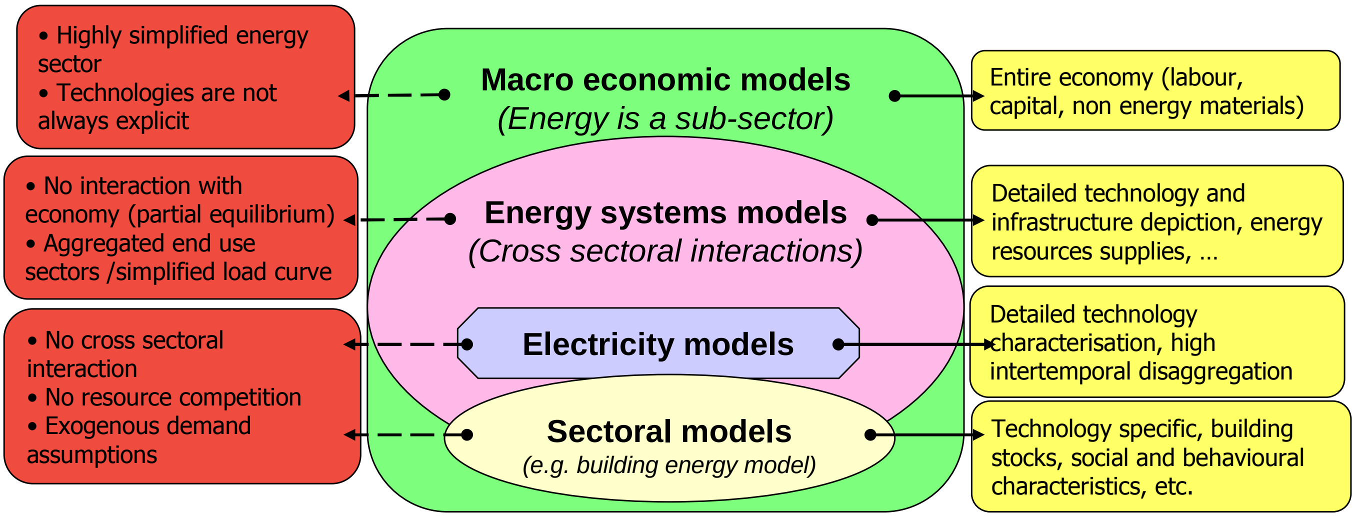

Figure 1: Overview of the existing Swiss modelling tools

To meet the growing Swiss energy demand [12] and achieving CO_2 emission reduction targets [13][40][23], a paradigm shift in energy supply/use is inevitable. Nonetheless, there is a high level of uncertainty about the direction and extent of the required change in terms of which resources and technology options will be most suitable. The Swiss energy system has a number of fairly unique features, and thus faces a different set of challenges to many other countries. For instance, the Swiss electricity system is currently dominated by carbon-free hydroelectric and nuclear generation. In addition, Switzerland experiences large differences in seasonal electricity demand and, as a consequence of the large contribution from hydroelectricity, seasonal electricity output. Moreover, Switzerland is highly integrated into the European electricity grid, and currently undertakes extensive diurnal and seasonal trading, complemented further by the availability of pumped storage. In the future new renewable technologies with intermittent and seasonally-variable output (such as solar and wind), or combined heat and power systems with seasonal operation may also play a role. Therefore, understanding possible transition pathways for the Swiss energy system over the medium and long term requires sophisticated analytical tools that can also account for seasonal and diurnal variations of energy supply options. Existing analytical tools are not able to respond to this need (see Figure 1). Therefore we are developing a flexible model which explicitly depicts plausible pathways for the development of the electricity sector, while dealing with inter temporal variations in demand and supply. The proposed name for this new model is the Swiss TIMES electricity systems model (STEM-E).

This development of an electricity system model will feed in to the development of an integrated model of the entire energy system, with the overall objective to have a ‘long-term’ Swiss energy ‘systems’ model with a well-balanced and detailed representation of energy sub-sectors. However, it is planned to adopt a modular approach that enables the electricity subsector model (described in this report) to be used as a standalone model for power sector analyses. The development of the integrated model of the full energy system, including other energy supply and end use sectors, is being developed with the support of the BfE [44].

1.1. TIMES modelling framework

TIMES (The Integrated MARKAL[1] EFOM[2] System) is a widely applied bottom-up, dynamic, linear programming optimisation modelling framework [36]. TIMES has the enhanced features from the EFOM and an integrated climate model. TIMES, like in its MARKAL forebear [37], has the capability to portray the entire energy system from resource supply, through fuel processing, representation of infrastructures, conversion to secondary energy carriers, end-use technologies and energy service demands at end use sectors. TIMES thus provides an ideal framework for developing a vertically integrated model of the entire energy system. However, TIMES is also suitable for modelling in detail single subsectors of the energy system, such as the electricity system. TIMES is a perfect foresight model, i.e. the participants in the system have *perfect* inter-temporal knowledge of the future demand, technology, policy, etc. Hence, TIMES determines the economy-wide

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[1] MARKAL (MARKet Allocation) is a cost optimization model based on life-cycle costs of competing technologies to meet an exogenously defined energy service demands. The MARKAL modelling framework is developed by the Energy Technology and Systems Analysis Program (ETSAP) of the International Energy Agency (IEA).

[2] EFOM (Energy Flow Optimization model) is an engineering oriented bottom-up model, which describes the energy system as a network of energy flows, by combining primary fuels, through conversion and transport technologies, to the demand for energy services or large energy consuming materials. In EFOM, the planning horizon is defined by a certain number of periods, generally of different length.

solution of cost-optimal energy market development, under a given set of input assumptions, generating a detailed set of outputs on the evolution of the energy system. The TIMES modelling framework has proven to be a useful tool for a range of applications and is being used increasingly for national, regional [3] and global analyses, e.g. IEA[3], IPCCC [19]. A key attribute of the TIMES optimisation process is a systematic approach to uncertainty. This is achieved through a “what-if” analysis that seeks to quantify sensitivities and tipping-points of moving between technology categories and energy pathways.

1.2. Swiss TIMES Electricity Model

One of the key attributes that distinguishes application of an energy model is its temporal detail. The temporal representation has three dimensions: (1) the model time horizon; (2) the length of each time period; and (3) the resolution within a year. The length of the time horizon is critical when the research is concerned with long-term supply and infrastructure developments needed to address long-term energy challenges (such as climate change or oil depletion). In contrast, a high level of inter-annual time resolution is very important when the energy system needs to accommodate variable demand and supply of energy commodities. For example, electricity is a highly time-dependent energy commodity because both energy and capacity demands must be met at every instant. Thus electricity dispatch models [30][26][17][39] often have high levels of time resolution, varying between a few minutes and an hour, although generally their time horizon is limited to a few days. Examples of dispatch models with longer (e.g. decade) timeframes compromise on other aspects of dispatch [25] to reduce computational complexity (such as by seasonal aggregation).

Energy systems models [36][37][51][21], on the other hand, conventionally adopt a long time horizon – a few decades, if not a century – but have a very limited inter-annual time resolution. This long time horizon is important for understanding long-term development pathways for the energy system, and accounting for the investment cycle of long lived technologies/infrastructures (e.g. pipelines, electric grid).[4] Clearly, uncertainties affecting the energy system increase over longer model time horizons, as we deal with uncertain future parameters like economic growth, technology development, and energy demands, necessitating sensitivity and ‘what-if’ type analyses in conjunction with long-term modelling.

Ideally, models of energy system development should combine a sufficiently long time horizon and an appropriate level of inter-temporal resolution for the given analysis. In practical terms, the tradeoffs between these two temporal dimensions are

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[3] The International Energy Agency’s biennial Energy Technology Perspective (ETP) [31] has been analysed with MARKAL modelling framework and the next ETP is expected to be analysed with a new TIMES model.

[4] For example, a technology-rich electricity model should have a time horizon of at least 40-70 years to consider an investment cycle of nuclear plant.

driven by computational limitations; data availability; the type of time-dependent variables; methodological limitations within the modelling framework; and so on. The review from Boqiang and Chuanwen [4] acknowledges the complexities in making reasonable long-term and short-term supply schedules. Importantly, the tradeoffs could also affect the model solutions, and thus it is important to find the right balance given the practical constraints and the specific analytical policy application.

Many existing modelling frameworks adopt an approach combining a long time horizon with a very limited resolution within each time period, to provide an approximation for representing electricity load curves. For example, the MARKAL framework [37] splits each time period into only six “time slices”, while imposing no limits on the overall time horizon (although requiring that each time period is the same length). Some energy system models like LEAP [51], POLES [21] and NEMS [38] have a simplified algorithm to approximate capacity demands, but they are not comparable to any power sector specific models. The limitations of MARKAL are overcome in the TIMES framework. The TIMES framework has the capacity to represent any number of inter-annual timeslices, and to specify unequal time periods (which enables the user to contemplate long horizons while still describing the near term in a higher level of temporal detail). The flexible timeslices allow a much more detailed representation of variations in energy demand and supply, including operating characteristics of specific technologies. The TIMES framework is also able to account for energy storage, for example facilitating the representation of pumped hydroelectric storage by which electricity can be stored during one timeslice and discharged during another. Notably, this storage feature is often not included in electricity dispatch models. However, the TIMES framework cannot fully replace a dispatch model because it cannot account for reliability and stochastic characteristic of technologies, forced outage, loss-of-load probability, expected energy not served, etc.[25].

The primary objective of developing the Swiss TIMES electricity systems model (STEM-E) is to generate insights on long term development of the electricity sector under a cost-minimization framework. At the same time, we test the suitability of the TIMES framework to substitute (to some degree) for a dispatch model, even though some features of electricity dispatch cannot be represented. STEM-E is intended:

1. to generate insights on *long term* evolution of the Swiss electricity system to meet an exogenously defined electricity demands while fulfilling secondary objectives like CO_2 abatement, strategies on technology portfolio, energy security constrains, etc.
2. to analyze the *electricity generation schedule at an hourly level* by accounting for availability and operational constrains of interconnected system elements
3. to generate estimates of marginal cost of electricity at an hourly interval, thereby differentiating the competing technologies from conventional ranking based on levelised cost
4. to elucidate issues pertaining to integration of intermittent renewable energy technologies
5. to analyse the role of dam and pumped hydro in balancing the power system

With further development, the model could be:

6. extended to account for demand elasticity, so that the impact of price induced behaviour on electricity demand and technology choice could be analysed

7. plugged-in to an energy systems model (as planned)
8. extended to analyse in detail the role of dam and pumped hydro in electricity trading with neighbouring countries

In line with the five primary objectives, we have calibrated STEM-E to historical data from 2000 to 2009. Key inputs include past and future electricity demands, existing technology stocks, domestic and imported energy resources (and potentials), technical and economic characteristics of the future electricity (and heat) generation technologies, etc. The physical, regulatory and policy aspects of the electricity system are depicted by user-defined constraints. These are designed such that the optimisation pathways occur under a realistic engineering and socio-economic framework. The key outputs from the model include, but are not limited to, primary energy supply, electricity generation mix, installed capacity, electricity system costs, hourly electricity generation schedule and marginal cost of electricity, CO_2 emissions and shadow prices, and so on.

2. Model development

The STEM-E is developed in the VEDA[5] interface [56]. The model database and file structure are described in Appendix I.

2.1. Model definition

Key model definition parameters include the number of regions, time horizon, number of inter-annual timeslices, discount rate, currency units, and so on.

2.1.1. Regions

STEM-E is a single region Swiss (*CH*) model, covering the entire Swiss electricity system from resource supply to end-use. A single external region (representing the rest of the world) is defined to account for imports and exports of energy commodities (e.g. electricity, gas, uranium). However, because of the importance of international electricity trade in the Swiss system, STEM-E has four explicit electricity interconnectors to represent the international trade with Austria (AT), Germany (DE), France (FR) and Italy (IT).

2.1.2. Time horizon

STEM-E has a time horizon of 100 years (2000 – 2110) in 14 unequal time periods. In TIMES, the middle of a time period is referred as milestone year, which is also the result reporting year (see Figure 3). The time periods are specified to a length of 2

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[5] The VErsatile Data Analyst is a software package dedicated to the analysis of data and results obtained from a broad variety of mathematical models or data bases. VEDA is a powerful and user friendly tool for the construction of analyst tables and graphs to help in the analysis of results from complex mathematical models [56].

years in the short term periods, to enable detailed-calibration to the historical data.[6] In the medium and long term, the period is specified to be between five and 20 years in length. Therefore, the number of year in each period varies between two and 20 years (Table 1). Since the declaration of time period in TIMES is flexible, these time periods can be easily changed, or an alternate milestone year could be introduced, for the future years to avoid recalibrations (see Section 8).

Table 1: Modelling time horizons in STEM-E

Period number	**Period length *(years)***	**Actual time periods**	**Milestone year**
1	1	2000 - 2000	2000
2	2	2001 - 2002	2001
3	2	2003 - 2004	2003
4	2	2005 - 2006	2005
5	2	2007 - 2008	2007
6	4	2009 - 2012	2010
7	5	2013 - 2017	2015
8	5	2018 - 2022	2020
9	6	2023 - 2028	2025
10	12	2029 - 2040	2034
11	15	2041 - 2055	2048
12	15	2056 - 2070	2063
13	20	2071 - 2090	2080
14	20	2091 - 2110	2100

2.1.3. Timeslice

In STEM-E, inter-annual timeslices are depicted at seasonal, daily and hourly levels. The number of timeslices is decided based on the key trends in Swiss electricity demand, and operational characteristics of supply technologies. Swiss hourly electricity data for the year 2008 [27] was analysed to understand the demand pattern and are eventually aggregated at four seasonal and three daily levels. Figure 2 shows the electricity demand pattern for the year 2008, and illustrates a large seasonal variation in demand, along with differences between weekday and weekend demands within each season. There is a considerable difference between the lowest and the highest demands across seasons (peaking around 2 GW higher on winter weekdays than in summer), between days of the week (weekdays vs. weekends), and even within each day. For example, on summer weekdays there is a very steep increase in demand of around 1.5 GW between around 6:00 am and the peak at close to 12:00 pm. Across the weekdays (not shown) there is some variation in load profile, but the shape of the load curves is more or less similar.

[6] The shorter time step would also enable scheduling retirement of short-lived end use technologies like car and refrigerator when the other energy sub-sectors were to be included.

On Saturdays and Sundays, the demand pattern is slightly different from the weekdays. On winter Saturdays, the peak load occurs at 12:00 – 1:00am and at a lower level than on weekdays. On summer Saturdays the demand pattern is similar to the summer weekdays except there is no large daytime peak. The large seasonal and weekly variations in electricity demand put limitations on operation of inflexible base-load power plants, e.g. nuclear. On the basis of average demands in 2008, annual base-load capacity in the Swiss electricity system should not exceed 4 GW (summer minimum demand) without allowing for export or load dumping. However, the winter peak demand is more than 7 GW, indicating that the system needs around 3.5 GW of flexible power plants to cope with the dynamic load curve (ignoring for the moment additional capacity for reserve margins and shorter-term peaks). Since Switzerland is gifted with flexible dam- and pumped-hydro storage resources, the highly fluctuating load demands are easily met today, and electricity is also exported during peak hour.

Based on the electricity load curve, four seasonal, three daily and 24 hourly time slices have been chosen for the STEM-E. Thus the model has 288 annual timeslices and Figure 3 illustrates the timeslice tree. Table 2 shows the seasonal descriptions and the hourly and weekly fraction of timeslices, *QHR(Z)(F)*.

2.1.4. Currency unit

The objective function of the model is the discounted electricity system cost over the entire time horizon (discounted to the year 2010). All cost data in the model are declared in 2010 Swiss Franc (CHF_{2010}). The exchange rates for currency conversion are adapted from Swiss National Bank [50], while deflators are taken from the Swiss statistical office [15].

The model uses a system-wide discount rate of 3% that reflects the long term real yields on confederation bonds plus an additional risk premium for energy sector investments [49]. This discount rate is applied to calculate the annuity on capital expenditure as well as to discount the system costs. A technology-specific discount rate can also be introduced for annuity calculation. The discount rate is one of the many variables to perform sensitivity analysis.

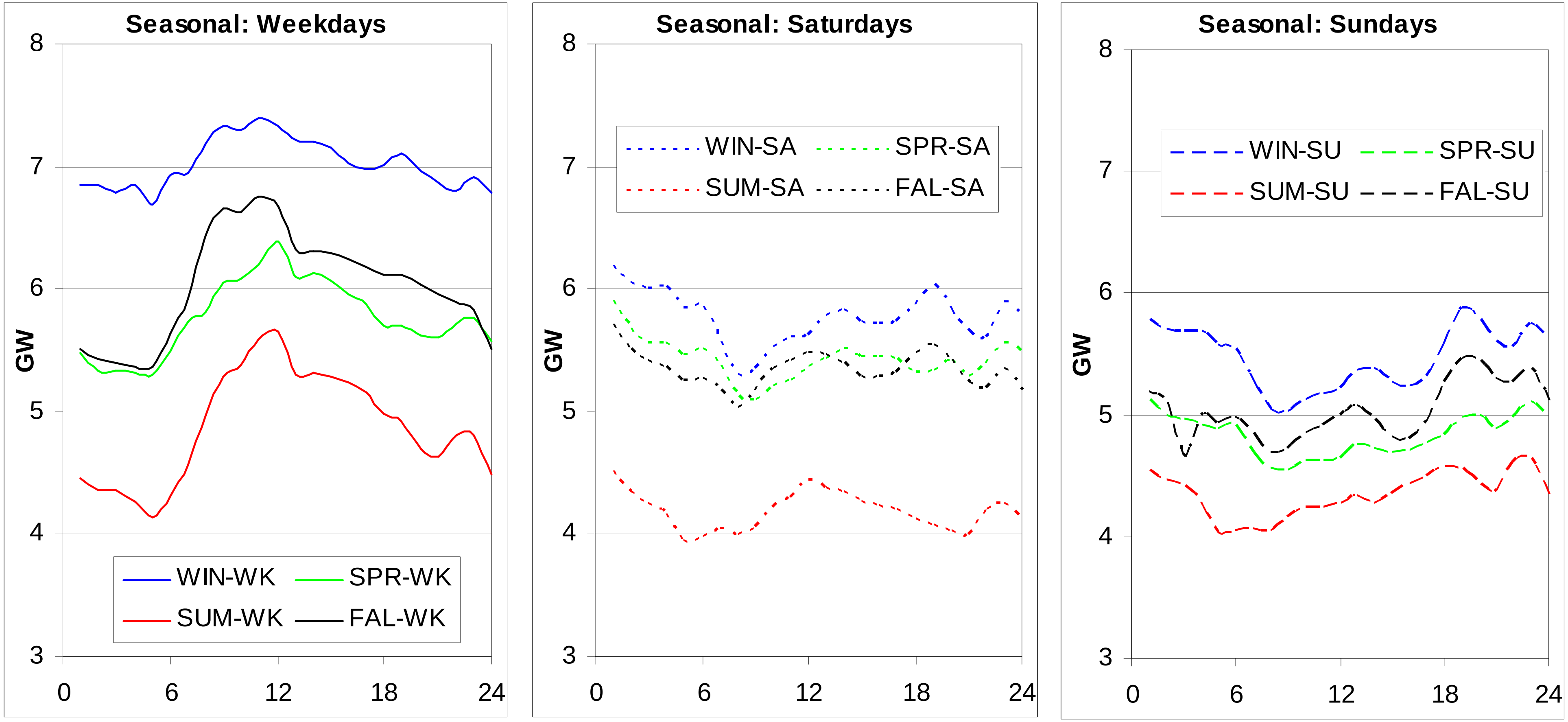


Figure 2: Seasonal and daily electricity load curves (2008)

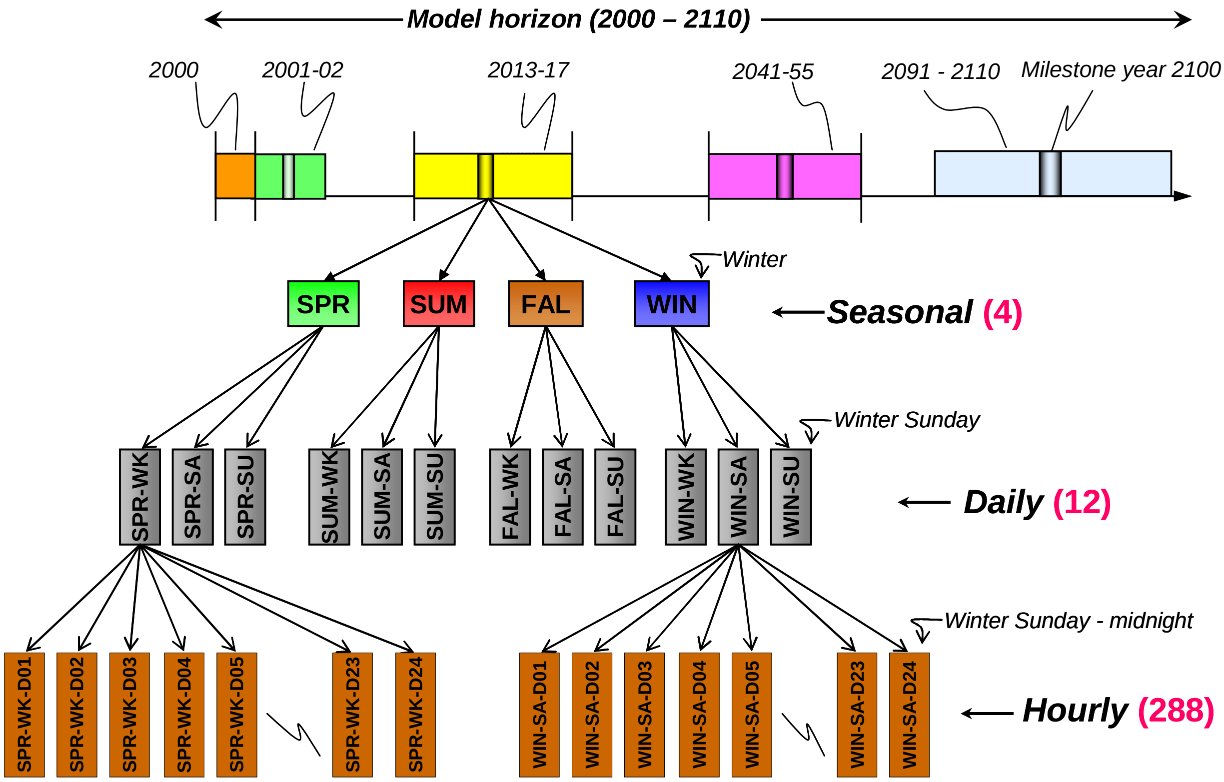


Figure 3: Inter-temporal details of STEM-E

Table 2: Definition of seasonal and inter annual timeslices in STEM-E

Seasonal	**Weekly days**	**Diurnal hours**
Summer (SUM-): *May - July*	Weekdays (WK-): *Monday - Friday*	D01, D02, D03 ………… D24
Fall/Autumn (FAL-): *August - October*	Saturdays (SA-): *Saturdays*	
Winter (WIN-): *November - January*	Sundays (SU-): *Sundays and Swiss national holidays*	
Spring (SPR-): *February - April*		

Weekly timeslices	**No of days**	**Weekly fraction**	**Hourly fraction**
WIN-WK-	63.5	17.4%	0.725%
SPR-WK-	63.5	17.4%	0.725%
SUM-WK-	63.5	17.4%	0.725%
FAL-WK-	63.5	17.4%	0.725%
WIN-SU-	15.5	4.2%	0.177%
SPR-SU-	14.5	4.0%	0.166%
SUM-SU-	14.5	4.0%	0.166%
FAL-SU-	14.5	4.0%	0.166%
WIN-SA-	13	3.6%	0.148%
SPR-SA-	13	3.6%	0.148%
SUM-SA-	13	3.6%	0.148%
FAL-SA-	13	3.6%	0.148%
	365	**100%**	

2.1.5. Computational and file structure

These key parameters described in Sections 2.1.1 to 2.1.4 are defined in the System settings file (see Appendix I). Some interpolation rules for data nodes are also described in the SysSettings file. The parameters in the SysSettings file are fixed and applied to all scenarios, though the discount rate can be overwritten through variant scenarios.

2.2. Reference energy system (RES)

A reference energy system (RES) interconnects energy resources, conversion technologies (in this case for electricity (and heat) generation) and end use demand through commodities[7]. Figure 4 illustrates a snapshot of the RES from STEM-E. The model has about 40 energy and emission commodities, like natural gas, uranium, CO_2 and so on. About 140 technologies[8] have been characterized. They include imported and renewable energy resource technologies; a range of existing and the future electricity generation technologies, including CHP; the electricity distribution grid; country-specific import and export interconnectors; and end-use demand technologies. Some of the commodities and processes are depicted only to track specific commodities or to facilitate flexible energy system configurations. A list[9] of commodities and technologies in STEM-E is given in Appendix III and Appendix IV.

Primary energy resources in the model comprise renewable and imported fuels, which are used as inputs to the electricity generation technologies. Electricity outputs from the electricity (and heat) generation technologies are distributed to five end use sectors. There is no heat demand in the model. In order to cope with operation of CHP, heat output from CHPs is currently modelled to be exported with small price incentive. CO_2 emission from fossil fuels is tracked at the resource consumption level. In the following sections the RES components are described from the end use sectors to supply side, i.e. right to left in the RES.

[7] In TIMES, commodities are classified under five commodity sets (Cset) via NRG (Energy), ENV (Emission), DEM (Demand), MAT (Material) and FIN (Financial).

[8] Process technology in TIMES refers to a wide range of technologies and are typically classified in the eight process sets (Pset) via ELE (Electric Power Plant); CHP (Combined Heat and Power); STG (Storage); PRE (Generic Process/Technology); DMD (Demand Device); IMP (Import); EXP (Export); MIN (Mining); RNW (Renewable) and HPL (Heat generating technology). Then, activity units (*Tact*) and capacity units (*Tcap*) are defined for each process. Optionally, operational flexibility of a technology can be characterized by linking their activity to timeslice (*Tslvl*). For example, base load power plant is commonly linked to ANNUAL while a flexible dam hydro power plant can be linked to DAYNITE. By default *Tslvl* is annual.

[9] The most updated list can be extracted from the model database (worksheet: *SEC_COMM* & *SEC_Processes* in *VT_STEM_ELC_v**.xls*).

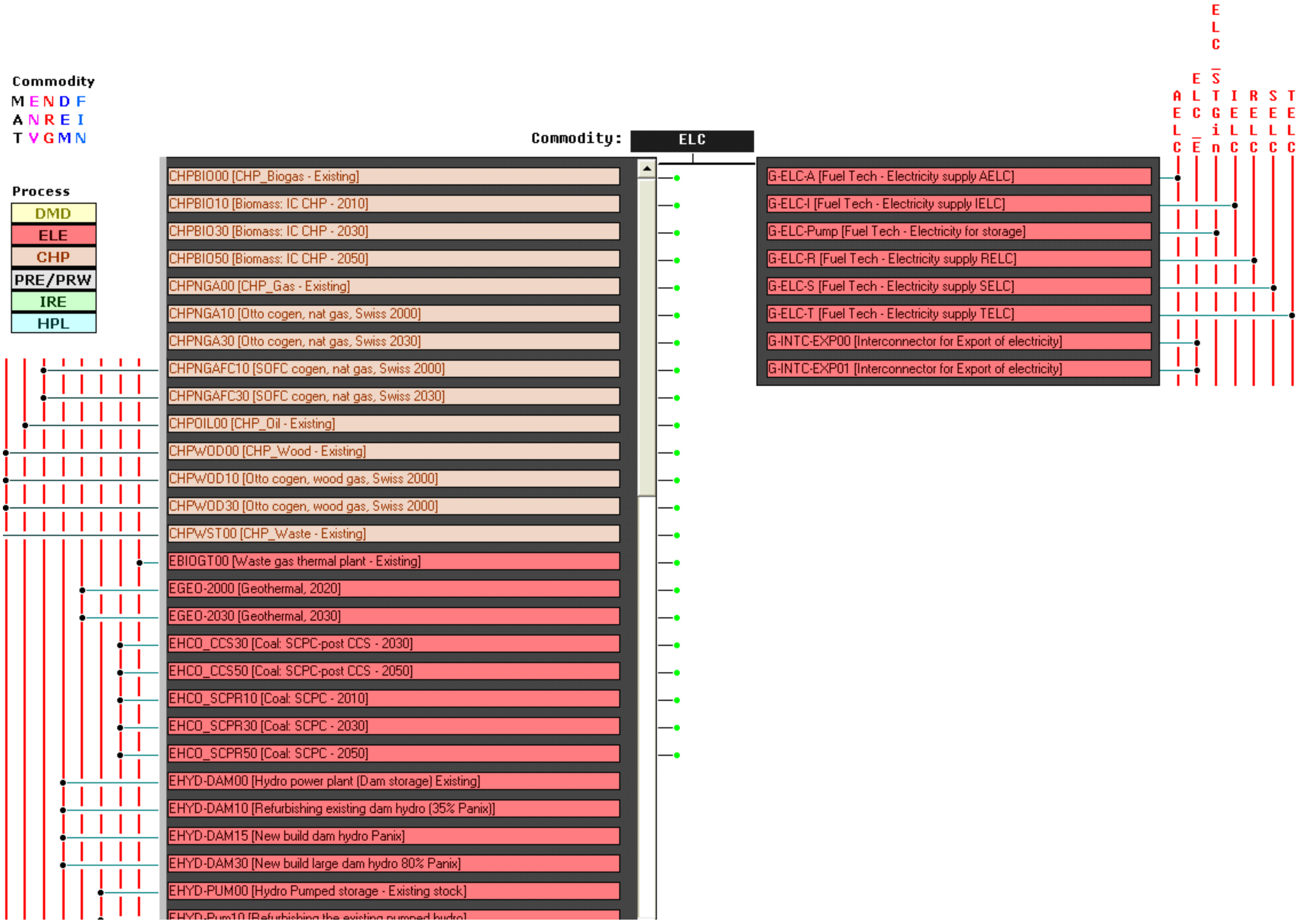


Figure 4: Illustration of RES in STEM-E

3. Electricity end use sectors

Electricity demand is modelled as energy service demand (ESDs) for five end-use sectors: residential (R), service (S), industry (I), transport (T) and agriculture (A). The explicit demand sectors provides the possibility to analyse sector-specific polices in the future—for example, in the future sectoral electricity demand could be endogenously linked to drivers like population growth, GDP, floor heating area, material output etc. Proximate electricity supply to the end use is depicted with dedicated electricity distribution grids and demand technologies. Other than the past electricity demand data (2000-10), future growth of electricity demands during 2010-2035 are adopted from the Energy Perspectives 2035 (Scenario – I) [12]. Electricity demand after the year 2035 is extrapolated according to the average annual growth rate between 2030 and 2035. Figure 5 shows the sectoral electricity demand assumptions in the model. Future electricity demand is, of course, uncertain and could be a target for scenario/sensitivity analysis.

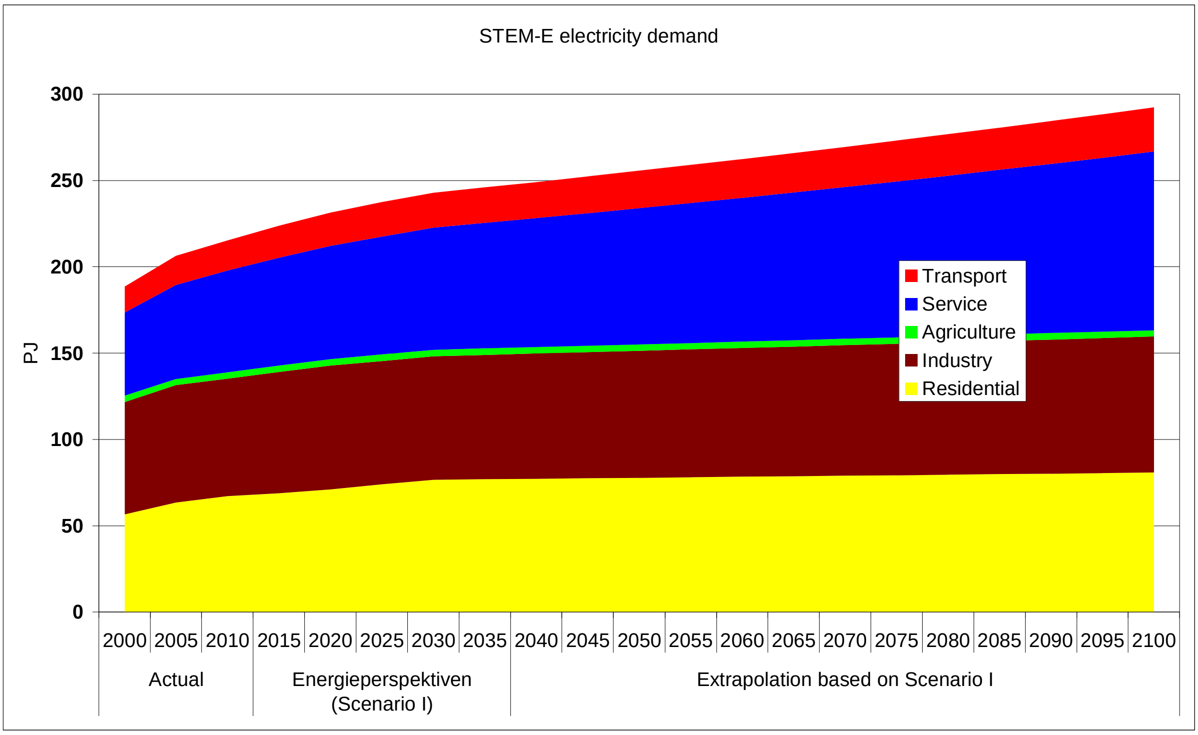


Figure 5: Sectoral electricity demand

For all the end use sectors, electricity demand is assumed to follow the Swiss national load curve. Thus, annual electricity demand from Figure 5 is distributed over the 288 timeslices (using the TIMES parameter FHR(Z)(Y), see Appendix II) based on the actual load curve in 2008. Analysis of the historical load curves (Figure 6[10]) reveals that the load profile has not changed significantly in the recent past even though the total electricity demand has changed. Thus, the year 2008 load curve is applied for the entire model horizon. However, demand from emerging transport technology (e.g. battery or plug-in hybrid vehicle), air conditioning, and fuel switching from oil to electricity for heating could affect this assumption. To analyse such cases, a variant load curve could be implemented. When the model is extended to the other end use sectors, this might not be an issue, as the electric load curve becomes endogenous. Nonetheless the energy service demand curve is still an exogenous input.

[10] It is worth of noting that Figure 6 is based on average demand of third Wednesdays in each month and Figure 2 is based on hourly demand data for the entire year. Therefore some variation in the peak profile is seen in the year 2008 load curve.

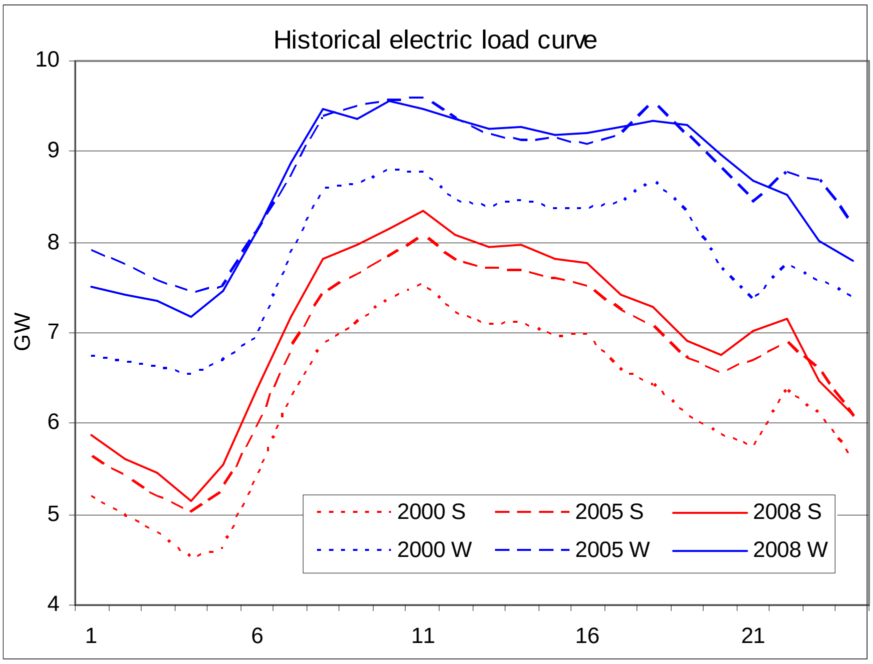


Figure 6: Historical electricity load curves (*based on third Wednesday demand*)

4. Electricity generation technologies

Electricity supply to the end use sector can be produced with a range of existing and new electricity (and heat) generation technologies. Both the electricity and heat conversion technologies in the model are described in the following subsections. Characterisation of electricity generation technology in TIMES is same as in the MARKAL framework (e.g. see Kannan (2009) [34]).

4.1. Existing technologies

All the existing electricity generation technologies up to the year 2009 are aggregated by fuel and technology [7]. A list of technologies, including the existing capital stock and technical characteristics is given in Table 3. In addition to the capacity, expected generation up to 2015 [7] is also included in the near-term calibration.

Table 3: Technology stocks in 2000 with their technical characterisation

Technology Name	Electrical efficiency	Installed Capacity in 2000 (*GW*)	Availability factor	Electricity generation in 2000 *(PJ)*	Peak load contribution
River hydro	80%	2.97	54.5%	51.00	90%
Small hydro	80%	0.70	55.4%	12.24	90%
Dam hydro	80%	8.07	27.6%	67.34	100%
Pumped hydro (storage)	80%	1.38	19.1%	5.69	100%
Nuclear plant Beznau I (1969)	30%	0.365	97%	9.01	90%
Nuclear plant Beznau II (1972)	30%	0.365	98%	10.97	90%
Nuclear plants Muhleberg (1972)	30%	0.355	95%	10.18	90%
Nuclear plants Goesgen (1979)	30%	0.970	95%	27.87	90%
Nuclear plant Leibstadt (1984)	30%	1.165	97%	31.77	90%
Solar PV	100%	0.015	14%	0.0389	0%
Wind turbines	100%	0.003	57%	0.0108	0%
Biogas plant	32%	0.01	57%	0.1375	30%
Waste incinerator	16%	0.31	57%	4.3542	30%
Gas Turbine	17%	0.00	43%	0.0202	100%
Waste wood thermal plant	33%	0.00	43%	0.0648	90%
Oil Engines	22%	0.26	43%	3.0798	50%
Gas CHP	13%	0.00	42%	0.0385	50%
Wood CHP	16%	0.13	43%	1.5422	50%
Biogas CHP	31%	0.04	14%	0.4298	50%
Oil CHP	18%	0.07	57%	0.7891	50%

Capacity factors for the existing technologies have been calculated for the past 10 years at individual or an aggregated cluster of technologies. The statistical average capacity factor is applied as the availability factor (of the existing technology) for the future years. Capital cost is not included for the existing capacity (since these plants are already in operation and fixed costs for interest or depreciation do not affect operation), but operation and maintenance (O&M) costs are accounted, using the same values as in the future technology data (Appendix VI).

4.1.1. Hydro power

Hydro power plants are aggregated in to three categories, i.e., river-, dam- and pumped-storage hydro. River hydro is further split into large and small river hydro based on ETS [18]. Installed capacity of hydro plants (capital stocks) is included in the model based on [11]. All hydro power plants are assumed to have a lifetime of 80 years, with existing plants retired (Table 4) based on their construction period [11]. The existing hydro plants can also be refurbished, which is assumed to cost 35% of new-build hydro plant (Table 9). The refurbishment is assumed to be replacement/ repair of existing equipments (turbine/generator) and / or desilting the reservoirs. Future hydro resource potentials are discussed in Section 5.

Table 4: Retirement schedule for hydro power plants

Total installed capacity (2008)	13.1	GW				
Assumed lifetime	80	Years				
Construction period [11]	Before 1945	1945-55	1955-65	1965-75	Post 1975	Today
Assumed years	**1945**	**1955**	**1965**	**1975**	**2010**	
Share of production capacity [11]	8%	11%	34%	18%	29%	100%
Cumulative share		19%	53%	63%	100%	
Estimated capacity	1.048	1.441	4.454	2.358	3.799	
Remaining lifetime	15	25	35	45	80	
Total capacity	1.048	2.489	6.943	9.301	13.1	
Residual capacity	**2010**	**2025**	**2035**	**2045**	**2055**	**2090**
Remaining capacity	13.1	12.052	10.611	6.157	3.799	0
% of today's residual capacity		92%	81%	47%	29%	0%

Historical electricity output from river hydro plants (Table 23, p-29, [7]) reveals that there is no large variation between weekdays and weekends (Figure 7). Therefore, the river hydro plant is characterised as a seasonal base-load plant, i.e. in a given season, it operates at a uniform load, subject to seasonal availability factors. Thus, seasonal availability factors are implemented as in Table 5.

The dam- and pumped hydro plants are characterised as flexible electricity generation technologies, subject to annual availability factors. However, for the dam hydro plants, a minimum and maximum availability factor is implemented at the daily level (Table 5), to reflect the current operational characteristics of hydro plants. Without these minimum availability factors, dam hydro plants could be operated only during the weekdays, because the electricity cost on weekdays is higher than on Saturdays and Sundays. On the other hand, the minimum operation of dam hydro plant fulfils any regulatory requirement on maintaining residual water flows in rivers.

The maximum and minimum availability factors are estimated based on monthly capacity factors shown in Figure 7.

Table 5: Availability of hydro power plants

Dam hydro plants								
	Maximum				**Minimum**			
	SUM	**WIN**	**FAL**	**SPR**	**SUM**	**WIN**	**FAL**	**SPR**
Seasonal	31.7%	21.6%	37.9%	8.8%				
Daily								
WK-	35.8%	30.2%	49.9%	27.5%	31.9%	25.0%	22.9%	20.9%
SA-	29.2%	18.5%	20.5%	19.8%	20.1%	9.1%	8.9%	9.3%
SU-	24.6%	11.7%	16.6%	17.1%	16.2%	7.8%	6.3%	7.1%
River hydro plants								
	SUM	**WIN**	**FAL**	**SPR**				
Seasonal	96.4%	36.5%	56.6%	62.1%				

For pumped hydro, a dedicated storage process is modelled and defined as inter-timeslice storage (STGTSS) technology. The output from the storage technology feeds the pumped hydro power plant. An additional grid technology is introduced before the storage technology to enable tracking the amount of electricity fed into the storage technologies.

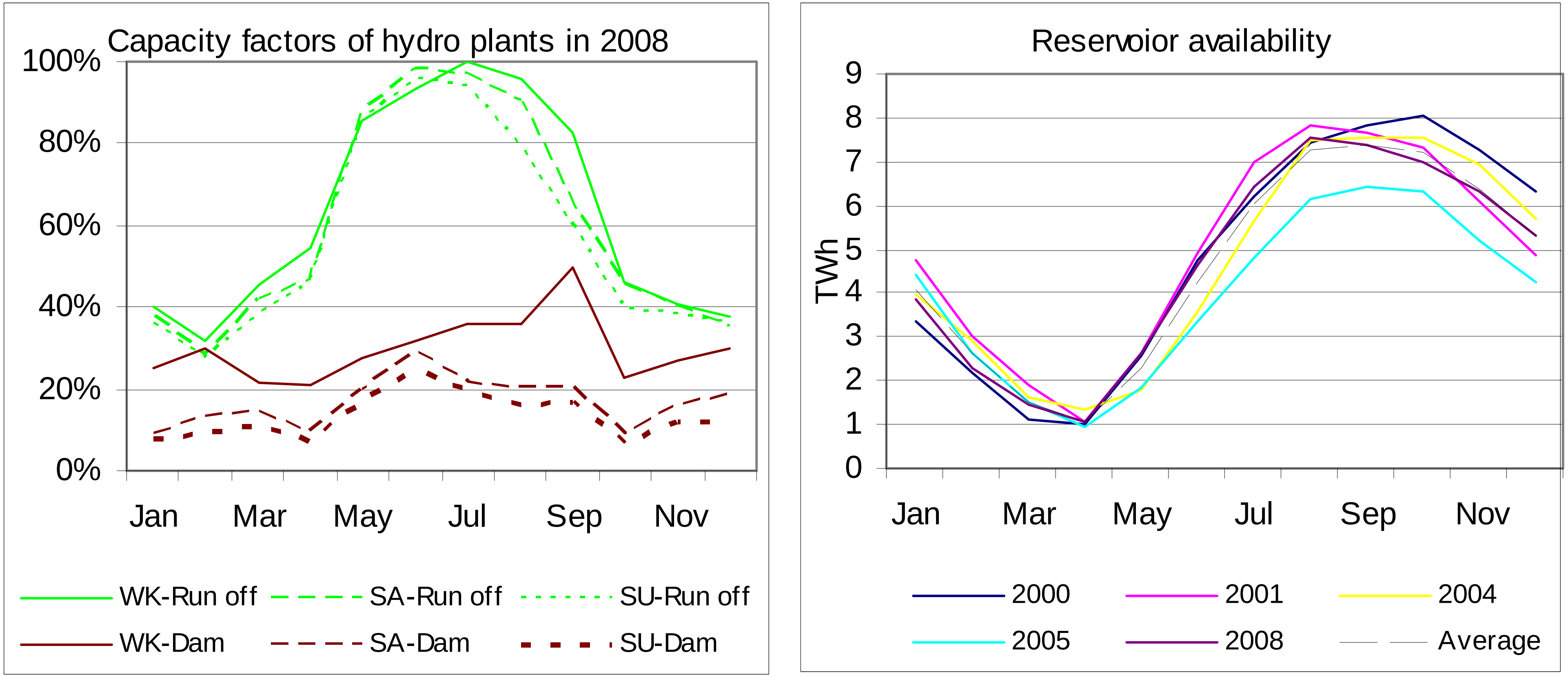


Figure 7: Capacity factor of hydro power plant and availability of hydro reservoir

4.1.2. Nuclear power

Nuclear plants are characterised as base-load plants. All the five existing nuclear plants, with a total capacity of 3.2 GW, are modelled individually based on historical generation data. The nuclear plants are assumed to retire 50 years after installation [22]. Thus, the first reactor at the Beznau is scheduled to retire in 2019 followed by the second reactor and the Muhleberg nuclear reactor in 2022. The Goesgen nuclear plant is scheduled to retire in 2029 followed by the Leibstadt nuclear plant in 2034. Historical capacity factors of individual plants were analysed [7] and shown in Figure 8. For the model the maximum capacity factor (Beznau I - 96%, Beznau II - 95.5%, Muhleberg - 95.1%, Goesgen - 94.3% and Leibstadt - 92.0%) is used as the availability factor for future years.

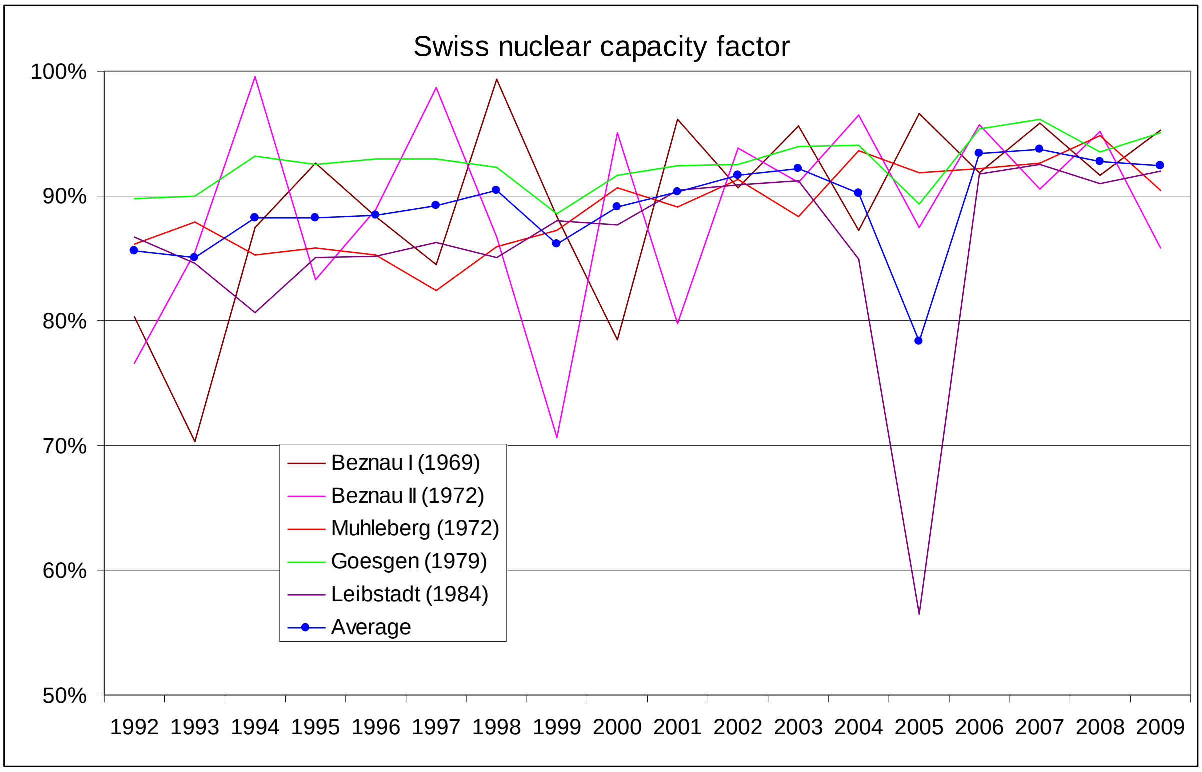


Figure 8: Historical capacity factors of nuclear power plants

Feedstock for nuclear plants is modelled as an imported fuel. The spent fuel from the nuclear reactor is not traced and therefore there is currently no cost associated with nuclear waste disposal in the model. However, Federal levy of 0.2 Rappen/kWh for the decommissioning funds (*Stilllegungsfonds für Kernanlagen*) and 0.8 Rappen/kWh for the disposal funds (*Entsorgungsfonds für Kernkraftwerke*) are modelled as tax on electricity from nuclear plants [14].

4.1.3. Thermal power

Existing thermal power plants in Switzerland comprise almost entirely oil, gas and biomass fired CHP plants; and waste incineration plants [9] (Table 6). The total installed capacity in 2007 was 852 MW. Electricity generation from these thermal plants and their fuel consumption were extracted from Swiss energy balances (Annex A.3 in [9]) and are given in Table 7. For CHP plants, only electrical efficiency is calculated and modelled with a commodity-specific efficiency parameter. However, in Table 3 only the electric efficiency is presented.

Capacity factors were calculated for each of the technology category for years 2000, 2005 and 2009 (e.g. Table 6). The same capacity factor is assumed for all fuel categories in Table 7 and implemented in the model for the remaining lifetime of each technology.

Table 6: Thermal and renewable power plants [9]

Plant type	2000			2009		
	MW	**GWh$_e$**	**Load factor**	**MW**	**GWh$_e$**	**Load Factor**
Oil	75	16	2.44%	75	18	2.74%
Waste gas	7.5	43.5	66.21%	1	5.2	59.36%
Incineration (KVA)	215	1131.9	60.10%	289.9	1560	61.43%
	297.5	**1191.4**	45.72%	**365.9**	**1583.2**	49.39%
CHPs						
KVA-CHP	47.4	152.4	36.70%	49.2	209.6	48.63%
Industry	261	916.4	40.08%	216	594	31.39%
District heat	74.5	102	15.63%	94.8	229	27.58%
Small CHP	126	472.5	42.81%	136	557	46.75%
	508.9	**1643.3**	36.86%	**496**	**1589.6**	36.58%
Sub-total	*806.4*	*2834.7*	*40.13%*	861.9	3172.8	42.02%
Renewable						
Solar PV	15	10.8	8.22%	45	34.4	8.73%
Wind	3	3	11.42%	13	18.5	16.25%
Total	**824.4**	**2848.5**	**39.44%**	**919.9**	**3225.7**	**40.03%**

As a near term calibration, the model is constrained to produce a minimum level of electricity from thermal plants till 2015 (Table 33, p.40 [7]). In addition, electricity production from gas-fired CHPs is assumed to continue until the retirement of the existing plants, and thus this minimum level of production is extended to 2020 for these plants.

Table 7: Electricity generation from thermal power plants by fuel

Plant type	**ELC outputs (2009)** [9]				
	OIL	***GAS***	***Waste***	***Wood***	***Other (gas)***
	In GWh				
Electricity only					
Thermal	18				
Waste gas					5.2
KVA	1	1.9	1557.6		
Sub-total	**19**	**1.9**	**1557.6**	**0**	**5.2**
CHPs					
KVA-CHP	0.4	9.3	198.5	1.5	
Industry	31.2	239.4	288.4	33.5	1.2
District heat	3.1	108.2		105	
Small CHP	39.4	427.3	0.1		185
Sub-total	**74.1**	**784.2**	**487**	**140**	**186.2**
Total	**93.1**	**786.1**	**2044.6**	**140**	**191.4**
	3255				
	Fuel inputs (2009) [9]				
Electricity only system					
Thermal	51.4				
Waste gas					17.1
KVA	5.7	11.1	9628		
Sub-total	**57.1**	**11.1**	**9628**	**0**	**17.1**
CHPs					
KVA-CHP	4.6	115.6	1746.4	13.6	
Industry	354.3	2104	1373.2	263.2	9.3
District heat	15.4	319.9		939.7	
Small CHP	117	961.4	0.2		587
Sub-total	**491.3**	**3500.9**	**3119.8**	**1216.5**	**596.3**
Total	**548.4**	**3512**	**12747.8**	**1216.5**	**613.4**
	18638				
	Estimated electric efficiency *(electricity output / fuel inputs)*				
Electricity only system					
Thermal	35%				
Waste gas					30%
KVA	18%	17%	16%		
	33%	**17%**	**16%**		**30%**
CHPs					
KVA-CHP	9%	8%	11%		
Industry	9%	11%	21%	13%	13%
District heat	20%	34%		11%	
Small CHP	34%	44%	50%		32%
	15%	**22%**	**16%**	**12%**	**31%**
	17%	**22%**	**16%**	**12%**	**31%**
Overall thermal system	**17%**				

4.1.4. Renewables

The existing renewable power plants (excluding hydro and biomass) comprise solar PV and wind turbines with an installed capacity of 46 MW in 2007 (Table 6). For these renewable electricity generation technologies, efficiency is nominally assumed to be 100%, but capacity and activity constraints are included in the model to reflect resource and engineering potentials (Table 12). Since the deployment of these renewables in the past might not have been driven by cost, a user-defined constraint is included to maintain the current low level of generation from solar PV and wind during the entire model horizon. The following subsection describes the depiction of renewable technology in the model. Swiss renewable potentials are discussed in Section 5.

Solar PV

Monthly availability of solar irradiation for selected locations (Zurich, Bern, Basel and Geneva) (Figure 9) and hourly solar irradiation for Zurich (Figure 10) were analysed for a tilt angle of 35 degree from the azimuth [33]. The monthly and hourly availability of the solar irradiation is normalized to an annual capacity factor of 11% for solar PV [29]. This hourly capacity factor is implemented as availability factor for solar PV at the hourly timeslice level (Figure 10).

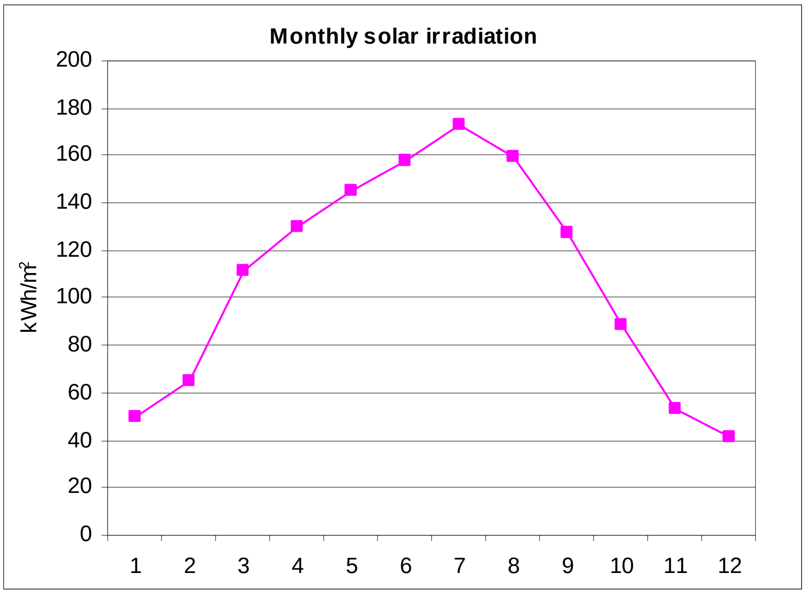


Figure 9: Swiss average monthly solar irradiation

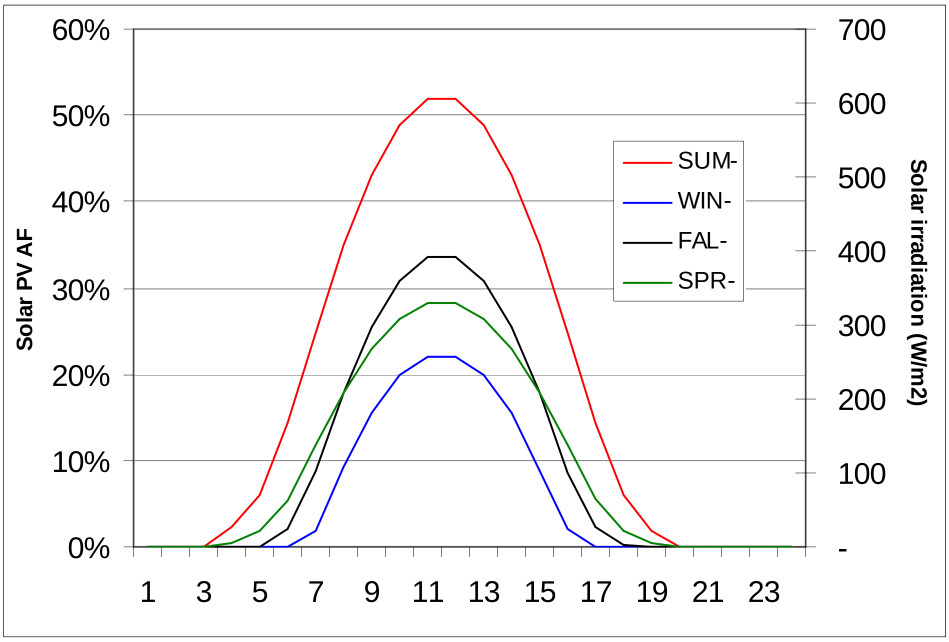


Figure 10: Hourly solar irradiation and solar PV availability factors

Wind energy

Wind turbines are characterised as seasonal base-load plant because hourly wind resource data are unavailable. Monthly average wind speeds from selected locations[11] in Switzerland [58] were analyzed (Figure 11). This revealed that wind speeds are generally higher in winter months compared to summer months. This trend is more prominent in high wind speed locations. Based on the monthly wind speed, the seasonal fraction of wind energy (i.e. square of the wind speed) was calculated. This seasonal fraction is normalised to the annual capacity factor of wind turbines (14%) to determine the seasonal availability factor implemented in the model (Table 8).

[11] With an annual average wind speed of 3.5 m/s and above is chosen because 3.5 m/s is the minimum cut off wind speed to run a typical wind turbine

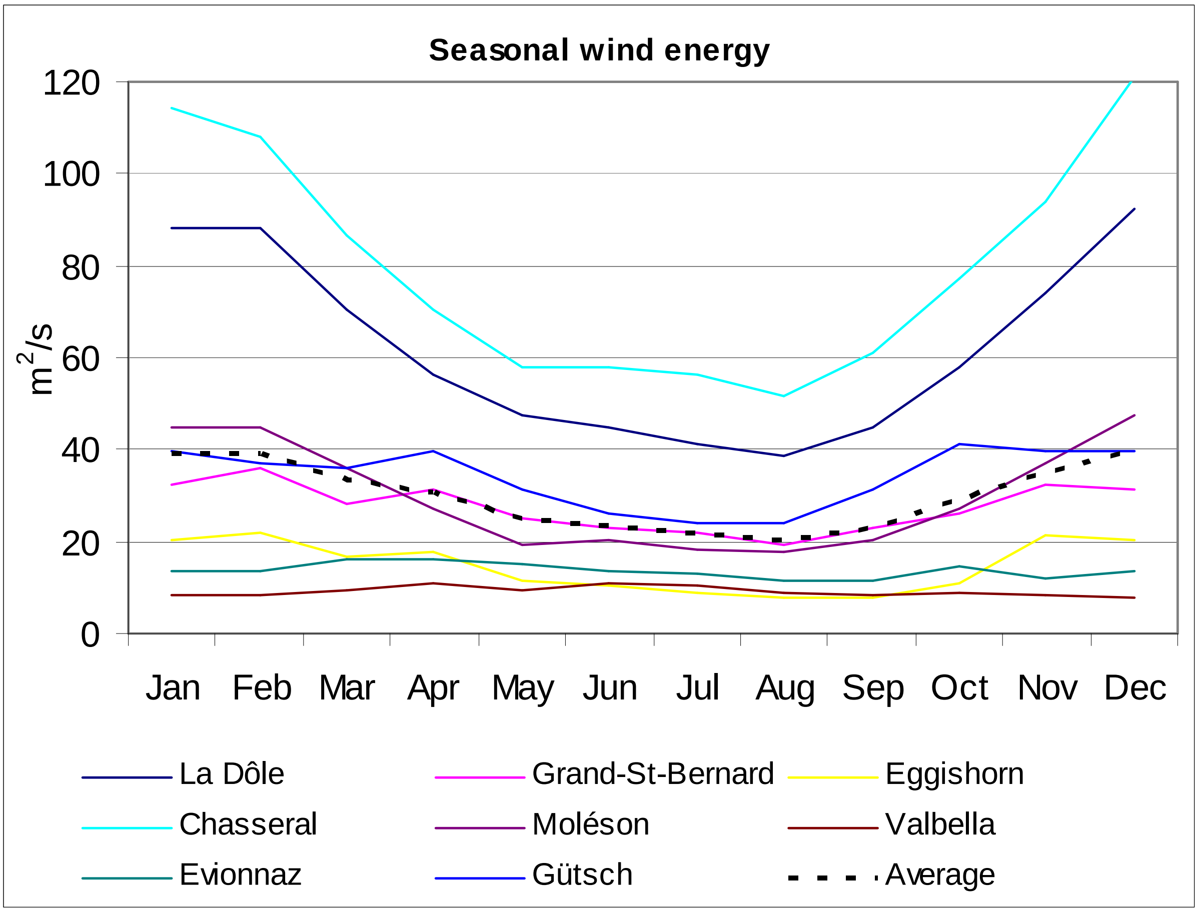


Figure 11: Seasonal wind speed variations

Table 8: Seasonal share of wind resource and availability factors

Season	Commodity fraction	Seasonal AF
Summer	18%	10%
Winter	32%	18%
Fall	25%	14%
Spring	25%	14%

Geothermal

Geothermal plants are characterised as base-load plants.

Biomass

Existing biomass plants are mainly CHP (see Table 7) and operation is mainly driven by heat demand. However, there is no heat demand in STEM-E (since it covers only the electricity sector). Nonetheless, all biomass and waste CHP plants are modelled as seasonal base load plants. Heat output from CHP is exported with small price incentive. Details of new biomass-based CHP plants are given in Table 9.

4.2. New and future technologies

New and future electricity generation technologies are introduced through SubRES scenarios (see Appendix I). All the existing technology categories are included. In addition, carbon capture and storage (CCS)[12] options are also modelled. The new and future technologies are introduced in three vintage years: 2010, 2030 and 2050. Technical and cost data of the new and future technologies are adopted from estimates of the PSI Technology Assessment Group [43].[13] Figure 12 illustrates the capital cost range of the new and future technologies between 2010 and 2050 and their efficiencies. The length of the cost bar indicates the cost reduction assumed between 2010 and 2050 (which could arise as a combination of learning and scale effects). For example, cost of solar PV is 6500 CHF/kW$_e$ in 2010 and it declines to 1950 CHF/kW$_e$ by 2050. Considering the uncertainties in cost data, a variant scenario with high technology costs was considered, i.e. a pessimistic cost assumption. A comprehensive summary of new and future technologies by category is given in Table 9, and details of individual technology vintages are provided in Appendix VI.

[12] Carbon capture and storage (CCS) pathways with explicit capture, transport and storage processes have been developed. Since efficiency of CCS is less than 90%, it does not help to look at scenario on zero carbon electricity. Thus CCS pathway is not fully implemented in the current version. Instead, for the time being, a 100% negative carbon is credited at electricity generation technology for scenario specific to zero carbon electricity.

[13] Note, technology cost and technical estimates are not interpolated between the vintage years (unlike the resource costs – see section 5). Instead, the old technology characteristics apply until the new vintage of technology becomes available.

Table 9: Technical characterisation and cost of new technologies

Technology description	Vintage Year*	Life time	Availability factor	Efficiency **	Capital Cost * #	FOM cost	VOM cost	Lead time***
		years	*%*	*%*	*CHF/kW*	*CHF/kW*	*CHF/GJ*	*years*
Hydro (large river) §	2010	80	65%	80%	6520	223	1.7	3
Hydro (small) §	2010	80	65%	80%	8200	223	1.7	
Hydro (dam) §	2010	80	28%	80%	10,000	11	1.8	3
Pumped hydro	2010	80	28%	80%	7000	11	1.8	3
Nuclear: Gen2 (LWR)	2020	50	91%	32%	4250 (5000)	23	3.3	6
Nuclear: Gen3 (EPR)	2030	60	91%	35%	4250 (5000)	12	1.9	6
Nuclear: Gen4 (FBR)	2050	40	90%	40%	4750 (8300)	55	0.2	6
Natural Gas: GTCC ##	2010	25	82%	58%	1150 (1400)	8	6.7	3
	2030	25	82%	63%	1050 (1300)	8	6.7	3
	2050	25	82%	65%	1050 (1300)	8	6.7	3
Natural Gas: GTCC-post CCS	2030	25	82%	56%	1700 (2000)	16	13.4	3
	2050	25	82%	61%	1500 (1800)	16	13.4	3
Solar PV	2000	40	11%	100%	6500 (8000)	5	0.6	
	2030	40	11%	100%	2850 (4000)	5	0.6	
	2050	35	11%	100%	1950 (3000)	5	0.6	
Wind	2000	20	14%	100%	2150 (2500)	44	13.9	
	2030	20	14%	100%	1750 (2000)	28	8.9	
Geothermal	2000	30	80%	40%	13825	134	12.4	3
	2030	30	80%	40%	6650	87	29.0	3
Interconnector	2010	50	80%	93%	434^	1.2^^	0.4^^	
CHP: Natural gas	2000	20	51%	32%	2650		9.7	
	2030	20	51%	42%	2100		6.9	
CHP: Biomass	2010	15	86%	36%	6000	180	10.3	
	2030	15	86%	42%	4200	126	5.4	
	2050	15	86%	44%	3800	114	5.4	
CHP: Biogas	2000	20	51%	32%	9682		16.9	
	2030	20	51%	42%	4833		9.8	

§ All the existing hydro power plants can be refurbished at a cost of one-third of the new build hydro plants.

* Technology cost and technical estimates are not interpolated between the vintage years. Instead, the old technology characteristics apply until the new vintage of technology becomes available.

** It's electrical efficiency. For CHP, overall efficiency of 80% has been assumed.

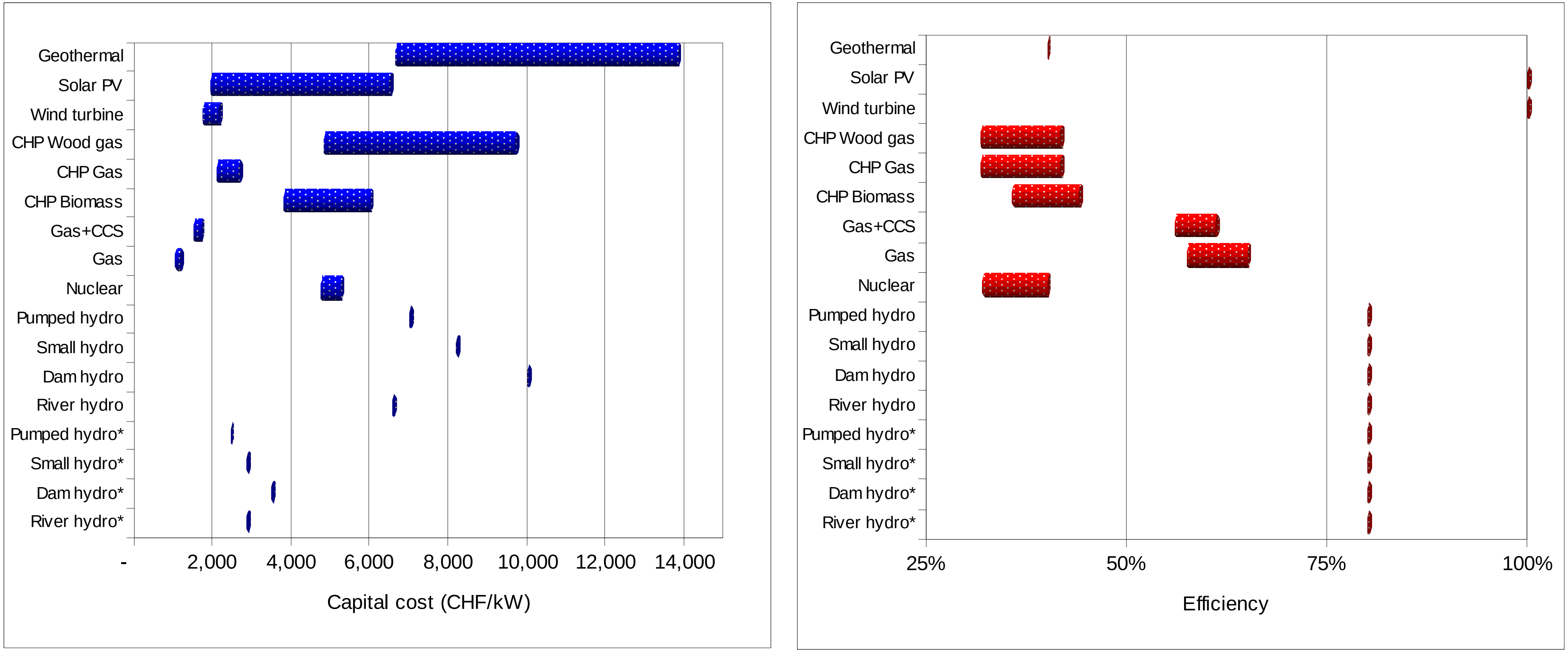
*** To account for construction time and interest during construction time.

High cost assumptions are given in parenthesis.

These are base load plants. For flexible (merit order) plants, we used same cost assumption, but efficiency and availability factor are reduced by 20% to reflect erupted operation

^ Based on Air cable interconnectors [41]

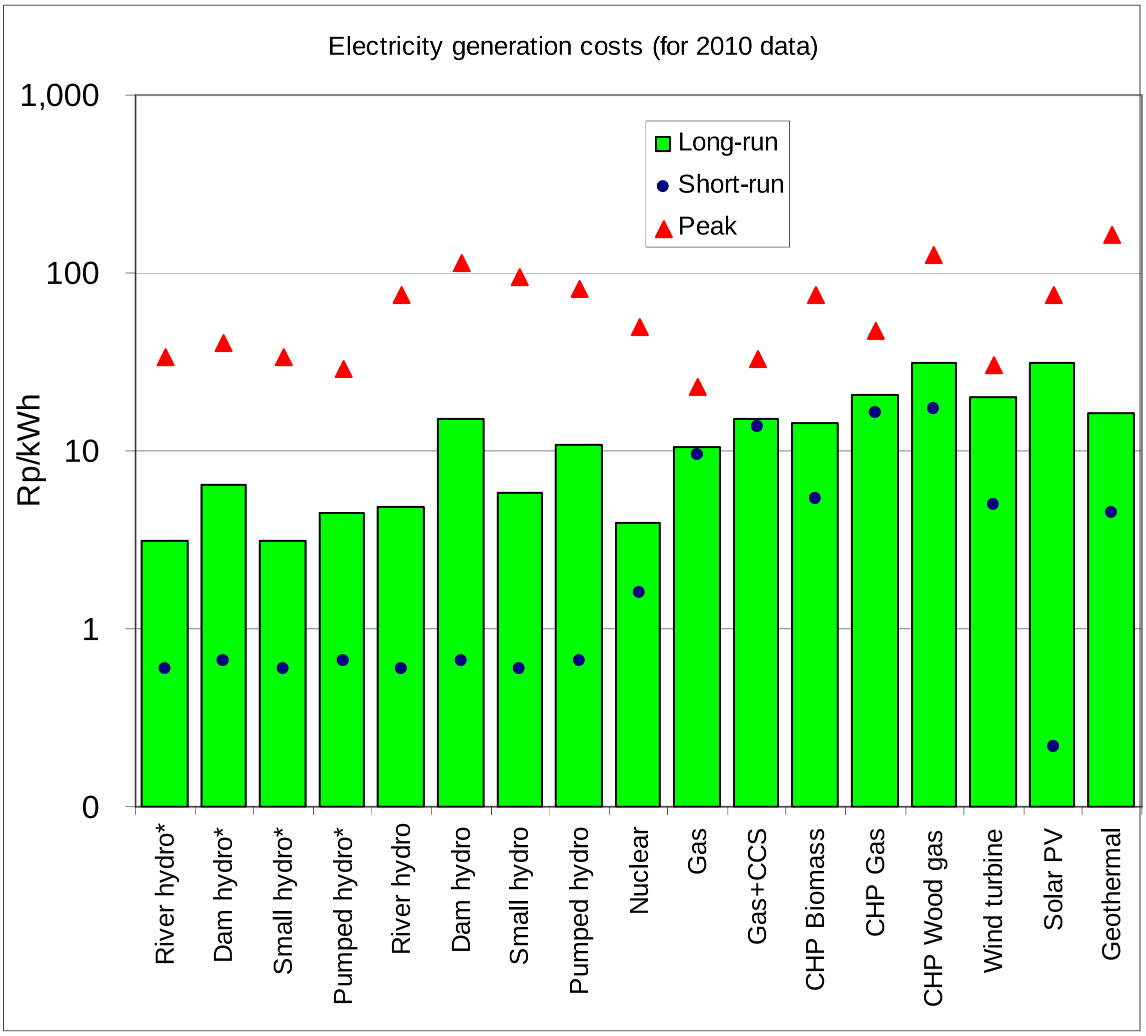
^^ Based on Swiss Grid [53] network usage charges



* Refurbishment of existing hydro power plants

Figure 12: Cost and efficiency of new electricity generation technologies

To make a rough estimate of the cost effectiveness of the new electricity generation technologies, we calculated three types of electricity generation costs: long-run marginal cost, short-run marginal cost and peak-time cost. They are calculated (Figure 13) based on the 2010 technology and resource costs using a discount rate of 3%. The long run cost is typically the levelised cost. The short-run cost is based on variable O&M cost and fuel costs only. The peak electricity cost is calculated to reflect cost of meeting a one-hour peak demand. It is calculated by assuming as if the entire capital cost is paid for this 1 kWh of electricity (and not amortised over the lifetime). It can be seen that capital intensive technologies have a high peak electricity cost. In practice, it is not only cost, but also flexibility that determines the suitability of a technology for covering short peaks in demand. Often, less capital-intensive gas turbines are preferred in such a role, but in Switzerland, flexible dam and pumped hydro plants are used (although we can see in Figure 12 that constructing a hydro plant purely for peak demand is unlikely to be cost-effective).



* Refurbishment of existing hydro power plants

Figure 13: Comparison of electricity generation costs (2010)

For all the large scale power plants, construction time is included in the model (see Appendix VI). The construction time accounts for lead times and interest costs incurred during the construction time. In TIMES, the capital cost is assumed to be paid uniformly during the construction time. Similarly, decommissioning time and cost are included.

5. Energy resources

Energy resources are depicted under three process sets (Pset): imports, exports and renewables. Details of the energy resources and cost assumptions are given in Table 12 All resource potentials are implemented by a linear interpolation between today's level and the years specified. Alternative assumptions could be considered here, such as enabling an early uptake of the full renewable potential (which could be appropriate for some policy scenarios with a strong emphasis on energy security, emission reductions and restrictions on other low-carbon options), which could be expected to affect model results.

Energy resource costs are specified for the years 2010, 2030, 2050 and 2100. For the unspecified years, the resource costs are linearly interpolated.

5.1.1. Hydro power

The electricity generation potential from hydro existing plants (Table 4) is adjusted to account for regulations on residual water flows, and for the impact on climate change based on [18]. The potential for new large-scale hydro plants is taken from [12][14] but adjustments are made for losses due to climate change and residual water flow similar to [18]. Small hydro potentials are taken from [18]. Table 10 shows the existing and new hydro potentials implemented in the model.

[14] Taken from *Erwartetes Ausbaupotenzial der Wasserkraft in der Schweiz* (p.100) in Die Energieperspektiven 2035 – Band 4, Exkurse [12]

Table 10: Hydro resource potentials

Hydro resources		2010	2015	2035	2050-2100
		In GWh			
Existing potential[#]	River	12395	12072	10777	10429
	Dam	20440	19906	17771	17198
	Small	3459	3290	2615	2520
	Sub-total (A)	**36294**	**35268**	**31162**	**30147**
New potentials[**]	Refurbishments/Efficiency improvements*		369	1601	1549
	River + Dam hydro[**]		637	2767	2710
	Small[#]		320	1395	1353
	Sub-total (B)		**1327**	**5764**	**5613**
	Remaining technical potentials (C)[***]		407	1762	1705
Total realizable potentials (***A*** + ***B***)		**36294**	**37001**	**38688**	**37464**
Total realizable potential by plant type	River	12395	12575	12961	12559
	Dam	20440	20410	19955	19328
	Small	3459	3610	4010	3873
		36294	**36595**	**36926**	**35760**
TOTAL potential (including *C*)		36294	37001	38688	37464
TOTAL potential (in PJ)		130	133	139	134

[#] Based on [18]
*Ausrüstungsersatz, Erneuerungen und Umbauten (Exkurse, p109 in [12])
** Neubauten KWK & GWK (Exkurse, p109 in [12])
*** Calculated from total technical potential (Exkurse, p109 in [12]) minus the new potentials (*B*)

5.1.2. Uranium

For nuclear reactors, uranium is assumed to be imported as fuel rods. Therefore, processing of uranium or fuel rod fabrication is not modelled. In addition, the disposal of spent fuel is not modelled. For the existing nuclear power plants and the new light-water reactors (EPR reactors – see Appendix VI), one single uranium supply curve is included. For new fast-breeder reactors (FBR, available from 2050), a new fuel resource supply is implemented due to differences in fuel cost to light-water reactor fuel.

5.1.3. Renewables

For non-hydro renewables, there is a wide range of estimates of resource potential indicating a high level of uncertainty. Some of the renewable potential data from literature are compiled in Table 11. The resource potentials assumed for STEM-E are discussed in the following subsections and summarised in Table 12.

Table 11: Renewable resource potentials

Resources	PSI [29] [42]		SATW (2007) [47]			ETS (2009) [18]		Other sources
	2004	*Long-term potentials*	*2003*	*Central range*	*Upper range*	*2006*	*Estimated potentials for 2050* §	
	TWh_e							
Hydro			34	36				6.28 # 1.1 (<10 MW) 1.1 – 1.8 (>10 MW)
Hydro (small)	3.4 (< 10 MW) 0.85 (< 1 MW)	In 2035: 5.8 (< 10 MW) & 1.1 (< 1 MW) 5.8 (< 10 MW) & 1.2 (< 1 MW)	0.3	1		3.5	4 – 5 (5.7)	
Solar PV	0.016** 21 MW_p	11 GW_p 9.4 – 13.7 TWh_e	0.017	5.7	13.3	0.02	8 – 12 (9.8)	
Wind	0.0054**	1.15 + 2.8 TWh_e (in 2050 p. 65)	0.005	1.2	4.0	0.02	2 – 3 (4)	1.5 (2030)/ 4 (2050) [46]
Biomass/ Biogas	26.1 TWh_t (2001)	83 91.94 TWh_t 331 PJ (Theoretical)	0.78	3.8	24.75* 8.25*	1.3	5 (9)	33 TWh_t [8] 2.6 TWh_e (2020) [57]
Geothermal	0	2 -3 TWh (2035) ** Very high		2.1	6.9		1.5 - 3.5 (5)	17 [59] 63 [59]##

§ The Energie Trialog working group made this estimation for the years 2035 and 2050 based on various studies and the group's expertise. The estimates from their reviews are given in parenthesis (refer Table 6, p. 59 in [18] for details)
# New hydro potentials based on [11]
Based on theoretical potential of 15.9 EWh (10^6 TWh) with a recovery rate of 4% and efficiency of 10 % [59]
* Biomass includes wastes and 25% of biomass is treated as biogas, mainly from waste water.
** Taken from Energiespiegel [42].

Solar PV

For solar PV, we have assumed a potential equivalent to 5.9 GW_p (20 PJ_e or 5.7 TWh_e) in 2050 and 14 GW_p (50 PJ_e 13.5 TWh_e) [47] in the model, which is consistent with [29][18].

Wind

A wind resource potential of 2.5 TWh by 2050 [18] (and 4 TWh by 2100 [47]) is implemented as a bound on the total electricity output of wind turbines.

Geothermal

A wide range of estimates on geothermal potential is available in the literature [18][47][59] (see Table 11. There is also significant uncertainty about the future role of geothermal due to political and technical uncertainties resulting from the failure of one of the first geothermal plants in Basel [28]. Thus, we are conservative on the short- and near-term potential. However, for long term, we assume a substantial potential is available. Thus, we implemented an electricity generation potential of 9 PJ_e (2.5 TWh_e) by 2050 based on SATW [47], increasing linearly to 61 PJ_e (17 TWh_e) by 2100 based on Axpo estimates [59].

Biomass

Biomass resources in the model include wood, biogas and wastes. Since biomass is also used in other end-use sectors—for example, residential heating—electricity generation from biomass-based technologies is constrained to a maximum of 13.7 PJ_e (3.8 TWh_e) based on SATW [47].

Electricity produced from waste incineration is limited to an annual growth of 0.1% from the 2010 level. In the literature [43][45] [57], waste is assumed to be a potential source for biogas. However, it is unclear how the waste sourced for biogas production reduces the waste stream available for electricity generation in incineration plants. Since the model is assumed to maintain the current level of waste incineration capacity, a maximum resource limit of 48 PJ_t is applied for waste and biogas combined, based on the 2009 level of waste use in electricity sector [9]. Future waste and biogas potential in 2100 is 10% above today's level.

Table 12: Energy resource potential and costs

Energy resources	**Costs 2010 – 2050*** (*CHF_{2010}/PJ*)	**Resource limits ***** (*PJ/year*)
Natural gas	11.46 – 18.62 [43]	
Uranium (fuel rod)	0.38 [43] 0.64 (for FBR) [43]	5 GW by 2050 8 GW by 2100
Electricity import/export	35.14 – 52.32 [1] (also see Section 6)	Max trade volume 250 PJ_e 15 GW (2050) / 21 GW (2100) For export, 20 GW (2050) / 26 GW (2100)**
Wastes and Biogas		48 PJ_t or 8 PJ_e (Maintained at 2009 level [7])
Biomass (wood)	9.7 – 7.10 [43]	83 PJ_t (2025) [29] 98 PJ_t (2040) [29] 122 PJ_t (2100) [29] 2.81 PJ_e (2010) [9] 13.68 PJ_e (2050) [47]
Hydro§	Existing	128 PJ_e (2010) 114 PJ_e (2050) [18]
	New	8.6 PJ_e (2015) 15.8 PJ_e (2050) [18][12]
Solar		20.52 PJ_e (6 GW) (2050) [47] 50 PJ_e (14 GW) (2100) [47]
Geothermal		9 PJ_e (2050) [18] 61.2 PJ_e (2100) [59]
Wind		9 PJ_e (2050) [18] 14.4 PJ_e [47]

*Cost data for 2100 is assumed from the 2050 cost with an annual cost escalation of 1%.
** Expert judgment (About 25% higher than historical average level)
*** Resource potential are linearly interpolated between the periods
# Biogas is assumed to be from waste
Including small hydro potential
§ Hydro potential are specified under three categories via river, dam and small hydro (see Table 10)

6. Electricity interconnectors

The Swiss electricity network is connected to the networks of the four neighbouring countries (Austria-AT, France-FR, Germany-DE and Italy-IT). In STEM-E, four country-specific electric import and export 'resources' are defined to represent these four markets. Each of these four resource technologies is linked to the Swiss network via dedicated interconnectors. These interconnectors have a total capacity of 13 GW export and 10 GW import [53]. Historically, electricity flow (trade volume) varies by country and season (Figure 14). The interconnectors are modelled as flexible technologies so that electricity can be traded at any time. However, based on the historical trade volume, seasonal availability factors are implemented for each of the interconnectors (Table 13). These seasonal availability factors are applied to the entire model horizon. This assumption could somehow restrict the model from flexible exchange of electricity in the future years, but the future availability of interconnectors is quite uncertain and heavily dependent on energy system development in the four markets.

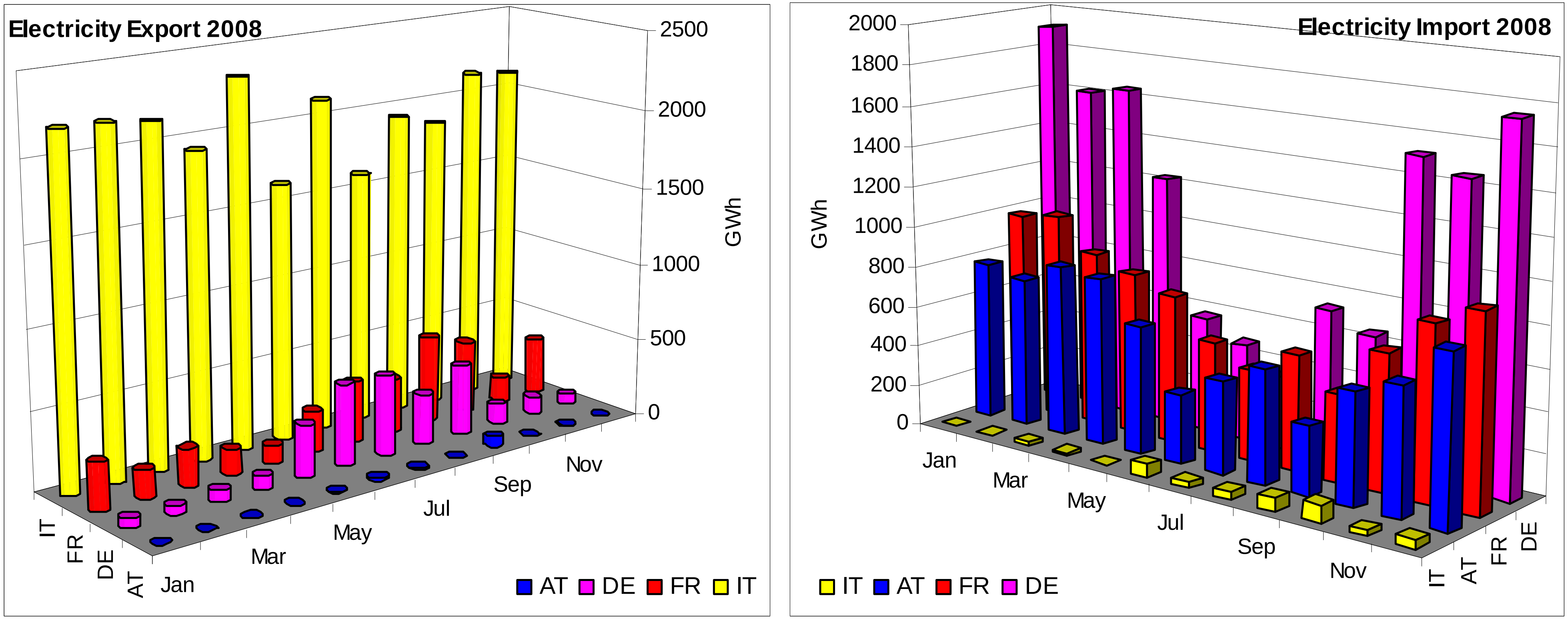


Figure 14: Regional electricity trade balance (2008)

Table 13: Historical availability of interconnectors and electricity market share

Seasonal availability factors					
Export	**AT**	**DE**	**FR**	**IT**	**Overall**
Summer	3%	18%	16%	57%	27%
Winter	0%	12%	17%	63%	26%
Fall	2%	11%	19%	61%	27%
Spring	5%	16%	8%	69%	28%
Import	**AT**	**DE**	**FR**	**IT**	**Overall**
Summer	37%	43%	59%	3%	36%
Winter	45%	59%	79%	2%	46%
Fall	38%	41%	78%	4%	39%
Spring	47%	49%	68%	1%	43%
Market share					
Export	**AT**	**DE**	**FR**	**IT**	
Max	0.7%	17.5%	11.6%	85.2%	
Min	0.3%	5.3%	5.6%	76.1%	
Average	0.6%	10.6%	8.7%	80.1%	
Import	**AT**	**DE**	**FR**	**IT**	
Max	24%	48%	40%	1%	
Min	18%	43%	27%	0%	
Average	22%	46%	32%	1%	

The capital cost of interconnectors is based on [41]. A variable O&M cost of 0.16 Rp/kWh (0.44 CHF/GJ) is included based on grid usage tariffs (Netznutzung Arbeitstarif) from Swiss Grid [53].

Much of the current international electricity trading appears to be through-trade to exploit price differentials in the countries bordering Switzerland. However, STEM-E is not intended to analyse electricity trading from this arbitrage perspective. Instead the objective is to account for the impacts of trading on the operational schedule of power plants, including the possibility to import cheap off-peak electricity, store this electricity via pumped storage, and export it during periods with higher prices. Accordingly, it is still necessary to account in the model for some of the international price drivers of electricity trading. However, there are large uncertainties along with high volatility in the electricity market price, and thus only a stylized representation of import price is implemented. We analysed the European electricity spot market price for 2008 (Figure 15) to calculate a set of cost coefficients (or multipliers) for each of the 288 timeslices. These are applied to the annual electricity import price to generate time-dependent electricity import prices for all the 288 timeslices. The annual import price was taken from analysis in the ADAM project [1].

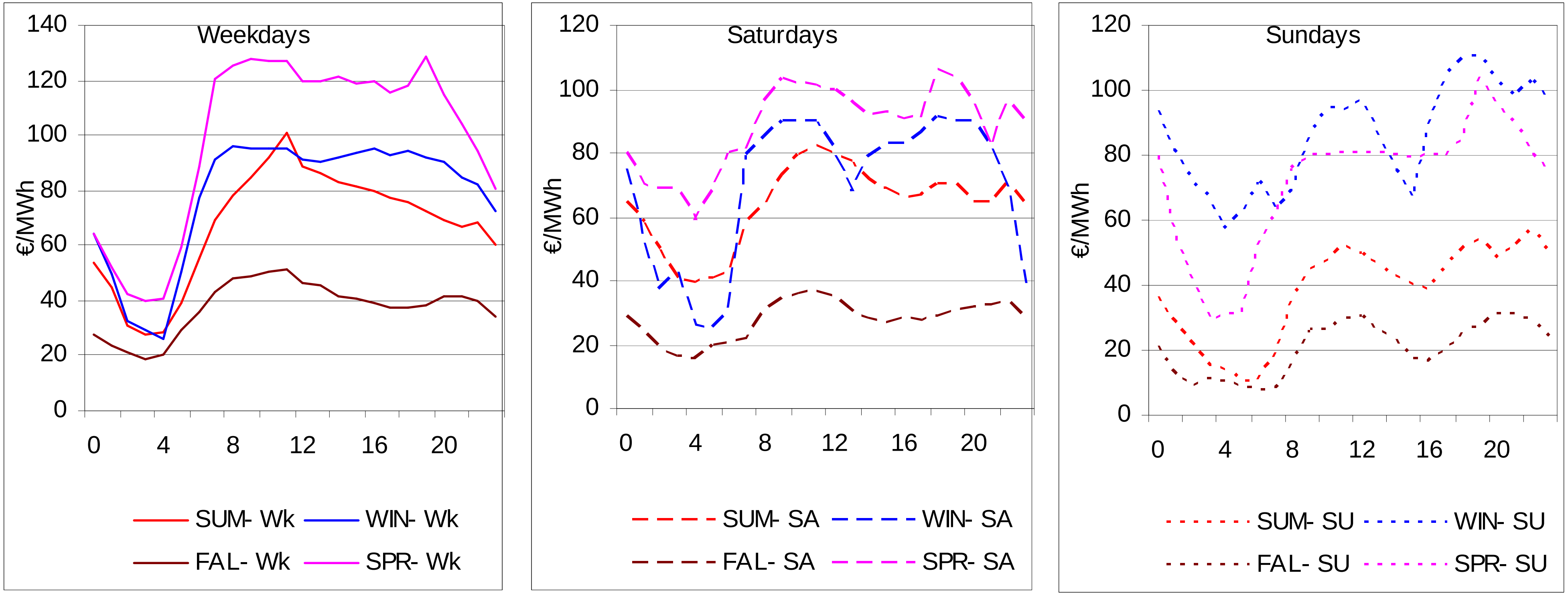


Figure 15: Swiss-German electricity spot market price

As an alternate approach to the spot electricity market, we used the electricity demand curves from the four countries to estimate country-specific prices for each timeslice. These estimates were derived by multiplying the annual electricity price by a timeslice coefficient. This coefficient is a linear function of the capacity demand, calculated from the fraction of annual demand in a given timeslice (*FHR(Z)(Y)*, for Switzerland see Appendix II) divided by the proportion of the year represented by the timeslice (*QHR(Z)(Y)* – see Table 2). Thus, if the hourly demand fraction is higher than the hourly fraction, the electricity cost at that time slice is also high and vice versa. The rationale for this approach is that electricity price increases with capacity demand. Figure 16 shows the hourly coefficient from five countries. However, the coefficient of Switzerland is shown only to demonstrate the relative change in all five markets with respect to the above methodology. The electricity export price is pegged to the import price at the timeslice level.

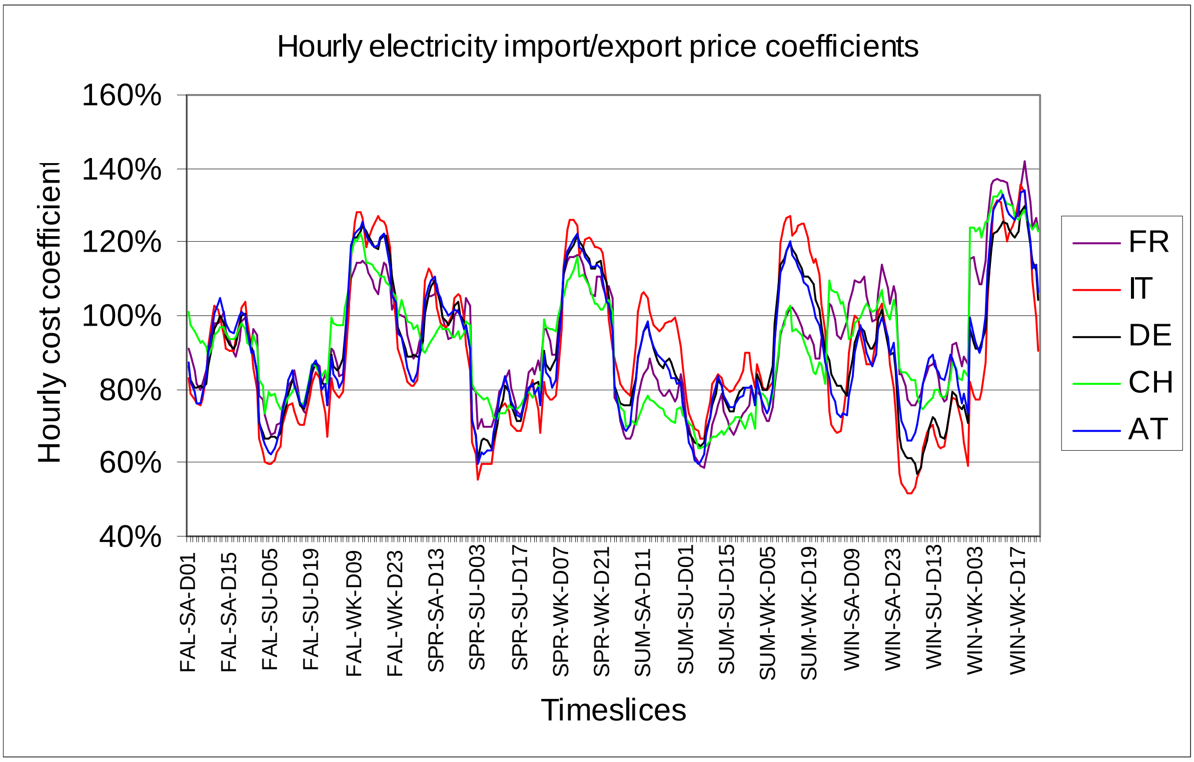


Figure 16: Hourly electricity import/export price coefficients

A minimum import and export of 50 PJ of electricity by 2015 is also implemented to smooth out the calibration year 2000-2010. In some scenarios, the model finds it cost-effective to build considerable capacity of interconnectors and large-scale base-load plants for electricity export. This is partly due to high export price assumption. Thus an upper bound on capacity of interconnectors is included. The capacity of all interconnectors is limited to 50% more than today's level by 2050 and 100% more by 2100. In addition, country-specific market shares are also implemented based on the historical trade volume (Table 13). With the limits on capacity, market share and seasonal grid availability factor, arbitrage-driven trade effects are curtailed. The combined electricity import and export volume is also limited to 250 PJ, which is 20% more than the recent historical trade volume.

An additional measure was implemented to reflect the historical self sufficiency of Switzerland in electricity trade over the year, but not necessarily in given seasons or shorter periods. This “self-sufficiency constraint” is introduced in such way that net electricity trade is roughly in balance over the year, but the timing of electricity trade is left unconstrained. This measure also helps to avoid excessive arbitrage-driven electricity trading.

7. Environmental emissions

CO_2 emissions from fossil fuels are traced at each resource-consuming technology using the CO_2 emission factors in Table 14. Non-fossil primary and secondary resources, e.g. biomass and imported electricity, are assumed to be carbon free.

Table 14: CO_2 emission factors

Energy commodity	**CO_2 emission *(t/TJ)***
Coal	91
Oil	78
Natural gas	56

8. Model calibration

The model is fully calibrated to the actual electricity supply and demand, generation mix and capital stock in the years between 2000 and 2010 [7][8]. As described in the previous sections, a number of constraints and bounds are included for near-term calibration until 2010 to reflect recent system characteristics. Thus the model has a range of user-defined constraints to reflect the historical operational patterns, technical and resources availability, market share, and so on.

Unfortunately, it has not been possible to obtain historical data at the level of hourly timeslices. Therefore, the model is calibrated to the annual electricity generation, but seasonal and weekly availability factors are included to imitate the historical electricity system characteristics. Figure 17 illustrates the load curve from the model (i.e. an output for year 2010) and the actual load curve (2008). The variation between the model and actual load curve on weekend is attributable to aggregation of Sundays and public holidays.

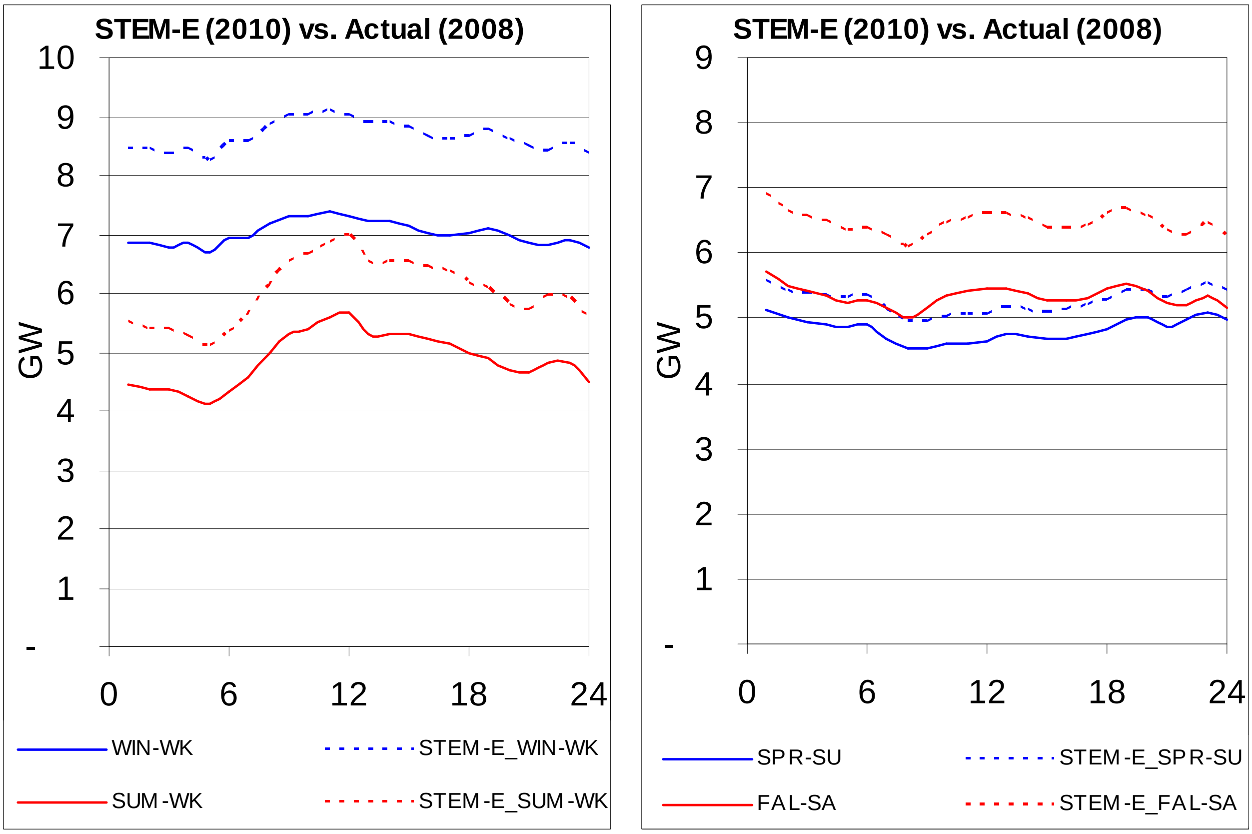


Figure 17: Actual electricity load curve versus the STEM-E outputs

9. Model application and outlook

The model has been applied to a range of policy analyses (for example, [35]), using the core data and assumptions documented here. However, as a least-cost optimization model used for scenario and sensitivity analysis to characterise uncertainty, each model run is carried out with a range of alternate data assumptions. Therefore, it is stressed that successive model applications may use alternate assumptions and this documentation should hence be viewed as a guide on model structure and not necessarily as a definitive description of data assumptions.

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Appendix I: STEM-E database file

The STEM-E is developed in VEDA - VErsatile Data Analyst. VEDA is a piece of software dedicated to the analysis of data and results obtained from a broad variety of mathematical models and databases. VEDA is a powerful and user-friendly tool for the construction of tables and graphs to help in the analysis of results from complex mathematical models [56]. The VEDA Front-End (VFE) is the interface between input data and model generator. Input data are fed from an Excel worksheet. The structure of the VFE database comprises of many Excel data files. It has a system settings file with model definitions; and one or more Excel data file(s) with historical energy and technology data for calibration periods, which are referred to as the base year (*B-Y*) template. A *Sub-RES* folder has data on new energy pathways and technologies. There is a *SuppXLS* folder that has data files for variant 'scenarios'. Through the variant scenarios, either new 'parameters' can be introduced or previously declared data can be overwritten. However, neither a new process nor new commodities can be introduced through the variant scenario. This can only be introduced in the *B-Y* or *Sub-RES* data files. On synchronization through VBE, a TIMES database is compiled (.mdb). The database can be reviewed in the RES navigator in VBE interface. The list of Excel data file in STEM-E is given in the following table. Some near-term calibration data have been compiled under the *SuppXLS* folder with subscript B_*, which are essential for all model runs. Activating the solve tab in VBE , model equations are generated and solved in GAMS.

The model outputs from GAMS are analysed in the VEDA Back-End (VBE). In VBE, a number of tables are customised to view model results variables by technology and commodity groups. Excel templates are developed to extract key results and graphs for presentation from the VBE tables. Another Excel template is developed for electricity generation schedule and marginal cost of electricity at the hourly level.

Model	**Swiss TIMES electricity model (STEM-E)**
Author	*Kannan Ramachandran*
Organisation	Energy Economics Group Laboratory for Energy Systems Analysis Paul Scherrer Institut, 5232 Villigen PSI, Switzerland.
Database Name	STEM-E-R1 (14 June 11)
Sectors	Electricity sector
Start Date	01.09.2009
Last update	14.06.2011
Reference	R. Kannan and H. Turton (2011) *Documentation on the development of the Swiss TIMES Electricity Model*, Paul Scherrer Institut, Switzerland
Status	**First Release (14 June 2011)**

Folder name	Data files name	Description of contents
STEM-E-R1 (14 June 11)	SysSettings.xls	Global parameters Model time horizon - 2000-2110 Number of annual timeslices (4 x 3 x 24 = 288) Discount rate 3%
	VT_CH_ELC_V57.xls	Base year RES data with existing technology stocks, load curve, electricity demands Calibration year - 2000-2008
SubRES_TMPL	SubRES_NewTechv9.XLS	New technology data from Energie Spiegel; All technical and cost details, including lead time and carbon credit for CCS @ 90% capture efficiency New electric interconnectors
SuppXLS	Scen_B_Resource.xls	Historical availability factor of electricity generation technologies (Solar, hydro, wind, nuclear); Energy resource potential - Energy resource limits, capacity and generation constraints Tax on Nuclear electricity (Ordinance on the Decommissioning Fund and the Disposal Fund);
	Scen_B_ResCosts.xls	Energy resource costs with single electricity import/export with shape function on Swiss load curve coefficient.
	Scen_B_ResCosts_REG.xls	Energy resource costs with country specific electricity import/export with shape function on load curve coefficient.
	Scen_CO2_S.xls	Stabilization of CO2 emission intensity at the 2000 level (CO2/kWh)
	Scen_CO2_Z.xls	Zero CO_2 emission by 2050 and beyond
	Scen_Discount10%.xls	Discount rate of 10% to overwrite the 3.5% in SysSettings
	Scen_Discount6%.xls	Discount rate of 6% to overwrite the 3.5% in SysSettings
	Scen_ELC-IMP-CO2.xls	Emission factor for imported electricity (i.e. imported electricity is not carbon free)
	Scen_ELC-MKTShare.xls	User constraints specifying market share of electricity import and export from four regions
	Scen_ELC-NoImp.xls	No import of electricity from 2020
	Scen_ELC-TradBal_0%.xls	To reflect self-sufficiency in electricity supply or supply security, a constraint is introduced in such a way that net electricity trade is roughly in balance over the year (reflecting recent experience). The timing of electricity trade is left unconstrained, but annual exports and imports are required to be in balance across the entire modeling time horizons.
	Scen_ELC-TradBal_25%.xls	In Scen_ELC-TradBal_0%, the self-sufficiency constraints is relaxed to import up to 25% of electricity demand
	Scen_LumpyInv.xls	Lumpy investment variants for nuclear technologies
	Scen_Min-Elc-Imp-Exp.xls	User constraints to force the model to smoothly phase out energy trading by 2110 from 2010 level
	Scen_MinHydro.xls	A constraint to invest on hydro power plants at least to maintain at today's level
	Scen_NoCentral.xls	User constraints to limit investment in large scale central plants (gas, nuclear)
	Scen_NoCoal.xls	User constraints to limit investment in coal power plants
	Scen_NoGas.xls	User constraints to limit investment in gas power plants, including CHPs
	Scen_NoNUC.xls	User constraints to limit investment in new nuclear plants

Appendix II: Electricity demand fraction – *FHR(Z)(Y)*

Diurnal hours	FAL			SPR			SUM			WIN		
	SA	SU	WK	SA	SU	WK	SA	SU	WK	SA	SU	WK
Hourly QHR(Z)(Y)	0.174%	0.148%	0.719%	0.174%	0.148%	0.719%	0.174%	0.148%	0.719%	0.174%	0.148%	0.719%
	FHR(Z)(Y)											
D01	0.150%	0.136%	0.723%	0.155%	0.134%	0.719%	0.119%	0.119%	0.584%	0.162%	0.152%	0.899%
D02	0.144%	0.134%	0.711%	0.149%	0.131%	0.701%	0.114%	0.117%	0.572%	0.159%	0.150%	0.898%
D03	0.142%	0.122%	0.707%	0.146%	0.130%	0.699%	0.111%	0.116%	0.571%	0.158%	0.149%	0.891%
D04	0.141%	0.131%	0.704%	0.146%	0.129%	0.697%	0.109%	0.112%	0.559%	0.158%	0.149%	0.898%
D05	0.138%	0.129%	0.704%	0.143%	0.128%	0.695%	0.104%	0.106%	0.543%	0.153%	0.146%	0.877%
D06	0.138%	0.130%	0.739%	0.145%	0.129%	0.720%	0.104%	0.106%	0.566%	0.154%	0.146%	0.909%
D07	0.136%	0.127%	0.778%	0.141%	0.123%	0.751%	0.106%	0.107%	0.599%	0.146%	0.139%	0.911%
D08	0.132%	0.123%	0.845%	0.135%	0.120%	0.763%	0.105%	0.106%	0.651%	0.139%	0.132%	0.942%
D09	0.136%	0.124%	0.875%	0.134%	0.119%	0.793%	0.106%	0.109%	0.694%	0.141%	0.132%	0.961%
D10	0.140%	0.127%	0.870%	0.136%	0.121%	0.798%	0.111%	0.111%	0.706%	0.145%	0.135%	0.958%
D11	0.142%	0.129%	0.887%	0.138%	0.121%	0.813%	0.113%	0.111%	0.732%	0.147%	0.136%	0.970%
D12	0.144%	0.131%	0.875%	0.141%	0.122%	0.839%	0.116%	0.112%	0.743%	0.147%	0.137%	0.961%
D13	0.143%	0.133%	0.830%	0.142%	0.125%	0.800%	0.115%	0.114%	0.696%	0.152%	0.141%	0.946%
D14	0.141%	0.130%	0.828%	0.144%	0.124%	0.805%	0.114%	0.112%	0.697%	0.153%	0.141%	0.946%
D15	0.139%	0.126%	0.825%	0.143%	0.123%	0.796%	0.112%	0.114%	0.694%	0.151%	0.138%	0.939%
D16	0.139%	0.126%	0.818%	0.143%	0.123%	0.781%	0.111%	0.116%	0.688%	0.150%	0.138%	0.921%
D17	0.140%	0.130%	0.811%	0.143%	0.125%	0.772%	0.110%	0.118%	0.677%	0.151%	0.140%	0.915%
D18	0.144%	0.138%	0.802%	0.140%	0.127%	0.748%	0.108%	0.120%	0.654%	0.154%	0.147%	0.921%
D19	0.145%	0.143%	0.803%	0.140%	0.131%	0.747%	0.107%	0.120%	0.645%	0.159%	0.154%	0.933%
D20	0.143%	0.143%	0.791%	0.142%	0.131%	0.737%	0.106%	0.116%	0.615%	0.153%	0.152%	0.914%
D21	0.138%	0.139%	0.782%	0.139%	0.128%	0.735%	0.105%	0.115%	0.608%	0.148%	0.147%	0.902%
D22	0.136%	0.138%	0.772%	0.142%	0.131%	0.750%	0.110%	0.121%	0.632%	0.147%	0.146%	0.893%
D23	0.140%	0.141%	0.764%	0.146%	0.134%	0.756%	0.111%	0.122%	0.630%	0.154%	0.151%	0.906%
D24	0.136%	0.134%	0.723%	0.144%	0.131%	0.731%	0.108%	0.114%	0.590%	0.152%	0.148%	0.891%

Appendix III: List of commodities in STEM-E

Commodity Set Membership	Commodity Name	Commodity Description	Unit	Timeslice Level
NRG	NGA	Natural gas	PJ	Daynite
NRG	OIL	Oil	PJ	Daynite
NRG	COA	Coal	PJ	ANNUAL
NRG	URN	Uranium	PJ	ANNUAL
NRG	URN_FBR	Uranium for FBR reactors	PJ	ANNUAL
NRG	HYDR	Hydro River flow	PJ	Season
NRG	HYDD	Hydro Dam water flow	PJ	Daynite
NRG	GEO	Geothermal energy	PJ	ANNUAL
NRG	SOL	Solar radiation	PJ	Daynite
NRG	WIND	Wind	PJ	Season
NRG	WST	Wastes	PJ	ANNUAL
NRG	WOD	Wood	PJ	ANNUAL
NRG	BIO	Biogas	PJ	ANNUAL
NRG	ELC_STGin	Electricity input for storage	PJ	DAYNITE
NRG	ELC_STGout	Electricity output for storage	PJ	DAYNITE
NRG	ELC_I	Electricity (Import)	PJ	DAYNITE
NRG	ELC_I-AT	Electricity (Import) - AT	PJ	DAYNITE
NRG	ELC_I-DE	Electricity (Import) - DE	PJ	DAYNITE
NRG	ELC_I-FR	Electricity (Import) - FR	PJ	DAYNITE
NRG	ELC_I-IT	Electricity (Import) - IT	PJ	DAYNITE
NRG	ELC_E	Electricity (Export)	PJ	DAYNITE
NRG	ELC_E-AT	Electricity (Export)	PJ	DAYNITE
NRG	ELC_E-DE	Electricity (Export)	PJ	DAYNITE
NRG	ELC_E-FR	Electricity (Export)	PJ	DAYNITE
NRG	ELC_E-IT	Electricity (Export)	PJ	DAYNITE
NRG	ELC	Electricity	PJ	DAYNITE
NRG	RELC	Electricity (RES)	PJ	DAYNITE
NRG	IELC	Electricity (IND)	PJ	DAYNITE
NRG	SELC	Electricity (SER)	PJ	DAYNITE
NRG	TELC	Electricity (TRA)	PJ	DAYNITE
NRG	AELC	Electricity (AGR)	PJ	Season
NRG	LTH	District heat	PJ	ANNUAL
ENV	CO2	Carbon dioxide	Kt	ANNUAL
ENV	ResCr	Renewable Electricity	Unit	ANNUAL
DEM	ESD-RES	Residential electricity demand	PJ	DAYNITE
DEM	ESD-SER	Service sector electricity demand	PJ	DAYNITE
DEM	ESD-TRA	Transport electricity demand	PJ	DAYNITE
DEM	ESD-IND	Industrial electricity demand	PJ	DAYNITE
DEM	ESD-AGR	Agriculture electricity demand	PJ	Season
DEM	ESD-LTH	District heat demand (for energy balance only)	PJ	ANNUAL

Appendix IV: List of technologies in STEM-E

Process Set Membership	Technology Name	Technology Description	Activity Unit	Capacity Unit	TimeSlice level of Process Activity
CHP	CHPBIO00	CHP_Biogas - Existing	PJ	GW	SEASON
CHP	CHPBIO10	Biomass: IC CHP - 2010	PJ	GW	SEASON
CHP	CHPBIO30	Biomass: IC CHP - 2030	PJ	GW	SEASON
CHP	CHPBIO50	Biomass: IC CHP - 2050	PJ	GW	SEASON
CHP	CHPNGA00	CHP_Gas - Existing	PJ	GW	DAYNITE
CHP	CHPNGA10	Otto cogen, nat gas, Swiss 2000	PJ	GW	SEASON
CHP	CHPNGA30	Otto cogen, nat gas, Swiss 2030	PJ	GW	SEASON
CHP	CHPNGAFC10	SOFC cogen, nat gas, Swiss 2000	PJ	GW	SEASON
CHP	CHPNGAFC30	SOFC cogen, nat gas, Swiss 2030	PJ	GW	SEASON
CHP	CHPOIL00	CHP_Oil - Existing	PJ	GW	SEASON
CHP	CHPWOD00	CHP_Wood - Existing	PJ	GW	SEASON
CHP	CHPWOD10	Otto cogen, wood gas, Swiss 2000	PJ	GW	SEASON
CHP	CHPWOD30	Otto cogen, wood gas, Swiss 2000	PJ	GW	SEASON
CHP	CHPWST00	CHP_Waste - Existing	PJ	GW	SEASON
DMD	AGRDMDT	Agriculture demand technology	PJ	GW	SEASON
DMD	INDDMDT	Industrial demand technology	PJ	GW	DAYNITE
DMD	LTHDMDT	District heat radiator	PJ	PJ/a	ANNUAL
DMD	RESDMDT	Residential demand technology	PJ	GW	DAYNITE
DMD	SERDMDT	Service sector demand technology	PJ	GW	DAYNITE
DMD	TRADMDT	Transport demand technology	PJ	GW	DAYNITE
ELE	EBIOGT00	Waste gas thermal plant - Existing	PJ	GW	ANNUAL
ELE	EGEO-2000	Geothermal, 2020	PJ	GW	ANNUAL
ELE	EGEO-2030	Geothermal, 2030	PJ	GW	ANNUAL
ELE	EHCO_CCS30	Coal: SCPC-post CCS - 2030	PJ	GW	ANNUAL
ELE	EHCO_CCS50	Coal: SCPC-post CCS - 2050	PJ	GW	ANNUAL
ELE	EHCO_SCPR10	Coal: SCPC - 2010	PJ	GW	ANNUAL
ELE	EHCO_SCPR30	Coal: SCPC - 2030	PJ	GW	ANNUAL
ELE	EHCO_SCPR50	Coal: SCPC - 2050	PJ	GW	ANNUAL
ELE	EHYD-DAM00	Hydro power plant (Dam storage) Existing	PJ	GW	DAYNITE
ELE	EHYD-DAM10	Refurbishing existing dam hydro (35% Panix)	PJ	GW	DAYNITE
ELE	EHYD-DAM15	New build dam hydro Panix	PJ	GW	DAYNITE
ELE	EHYD-PUM00	Hydro Pumped storage - Existing stock	PJ	GW	DAYNITE
ELE	EHYD-Pum10	Refurbishing the existing pumped hydro	PJ	GW	DAYNITE
ELE	EHYD-PUM30	Hydro: Hydro-storage dam - 2010	PJ	GW	DAYNITE
ELE	EHYD-RUN00	Hydro power plant (Run of river) Existing	PJ	GW	SEASON
ELE	EHYD-RUN10	Refurbishing existing river hydro (35% Wildegg-Brugg)	PJ	GW	SEASON
ELE	EHYD-RUN15	New build river hydro (80% Wildegg-Brugg)	PJ	GW	SEASON
ELE	EHYD-SML00	Small river hydro plant Existing	PJ	GW	SEASON
ELE	EHYD-SML10	Refurbishing existing dam hydro (35% Panix)	PJ	GW	SEASON
ELE	EHYD-SML15	New build small hydro (Wildegg-Brugg)	PJ	GW	SEASON

Process Set Membership	Technology Name	Technology Description	Activity Unit	Capacity Unit	TimeSlice level of Process Activity
ELE	ENGA_CCS50	Natural Gas: GTCC-post CCS - 2050	PJ	GW	ANNUAL
ELE	ENGA_GTCC10	Natural Gas: GTCC - 2010	PJ	GW	SEASON
ELE	ENGA_GTCC30	Natural Gas: GTCC - 2030	PJ	GW	SEASON
ELE	ENGA_GTCC50	Natural Gas: GTCC - 2050	PJ	GW	SEASON
ELE	ENGA_GTCC-F-10	Natural Gas: GTCC - FLEX-2010	PJ	GW	DAYNITE
ELE	ENGA_GTCC-F-30	Natural Gas: GTCC - FLEX-2030	PJ	GW	DAYNITE
ELE	ENGA_GTCC-F-50	Natural Gas: GTCC - FLEX-2050	PJ	GW	DAYNITE
ELE	ENGAGT00	Opens Gas Turbine - FLEX	PJ	GW	DAYNITE
ELE	ENUCBEZ69	Nuclear plant Beznau I (1969)	PJ	GW	ANNUAL
ELE	ENUCBEZ72	Nuclear plant Beznau II (1972)	PJ	GW	ANNUAL
ELE	ENUCGOS79	Nuclear plants Goesgen (1979)	PJ	GW	ANNUAL
ELE	ENUCLEB84	Nuclear plant Leibstadt (1984)	PJ	GW	ANNUAL
ELE	ENUCMUL72	Nuclear plants Muhleberg (1972)	PJ	GW	ANNUAL
ELE	EOilENG00	Oil Engines	PJ	GW	DAYNITE
ELE	ESOLPV00	Solar PV - Existing stock	PJ	GW	DAYNITE
ELE	ESOLPV10	Solar: PV-building - 2010	PJ	GW	DAYNITE
ELE	ESOLPV30	Solar: PV-building - 2030	PJ	GW	DAYNITE
ELE	ESOLPV50	Solar: PV-building - 2050	PJ	GW	DAYNITE
ELE	EWIND00	Wind generator - Existing	PJ	GW	SEASON
ELE	EWIND10	Wind: Wind-onshore - 2010	PJ	GW	SEASON
ELE	EWIND30	Wind: Wind-onshore - 2030	PJ	GW	SEASON
ELE	EWIND50	Wind: Wind-onshore - 2050	PJ	GW	SEASON
ELE	EWSTINC00	Waste incinerator - Existing stock	PJ	GW	SEASON
ELE	EWSTINC10	Waste incinerator	PJ	GW	SEASON
ELE	G-ELC-A	Fuel Tech - Electricity supply AELC	PJ	GW	SEASON
ELE	G-ELC-I	Fuel Tech - Electricity supply IELC	PJ	GW	DAYNITE
ELE	G-ELC-Pump	Fuel Tech - Electricity for storage	PJ	GW	DAYNITE
ELE	G-ELC-R	Fuel Tech - Electricity supply RELC	PJ	GW	DAYNITE
ELE	G-ELC-S	Fuel Tech - Electricity supply SELC	PJ	GW	DAYNITE
ELE	G-ELC-T	Fuel Tech - Electricity supply TELC	PJ	GW	DAYNITE
ELE	G-INTC-EXP00	Interconnector for Export of electricity	PJ	GW	DAYNITE
ELE	G-INTC-EXP00-AT	Interconnector for Export of electricity-AT	PJ	GW	DAYNITE
ELE	G-INTC-EXP00-DE	Interconnector for Export of electricity-DE	PJ	GW	DAYNITE
ELE	G-INTC-EXP00-FR	Interconnector for Export of electricity-FR	PJ	GW	DAYNITE
ELE	G-INTC-EXP00-IT	Interconnector for Export of electricity-IT	PJ	GW	DAYNITE
ELE	G-INTC-IMP00	Interconnector for Import of electricity	PJ	GW	DAYNITE
ELE	G-INTC-IMP00-AT	Interconnector for Import of electricity-AT	PJ	GW	DAYNITE
ELE	G-INTC-IMP00-DE	Interconnector for Import of electricity-DE	PJ	GW	DAYNITE
ELE	G-INTC-IMP00-FR	Interconnector for Import of electricity-FR	PJ	GW	DAYNITE
ELE	G-INTC-IMP00-IT	Interconnector for Import of electricity-IT	PJ	GW	DAYNITE

Process Set Membership	Technology Name	Technology Description	Activity Unit	Capacity Unit	TimeSlice level of Process Activity
ELE,DSCINV	ENUC_EPR30	Nuclear: Gen3 (EPR) - 2030	PJ	GW	ANNUAL
ELE,DSCINV	ENUC_FBR50	Nuclear: Gen4 (FBR) - 2050	PJ	GW	ANNUAL
ELE,DSCINV	ENUC_LWR10	Nuclear: Gen2 (LWR) - 2010	PJ	GW	ANNUAL
EXP	EXPELC_AT	Export electricity_AT	PJ	PJ/a	DAYNITE
EXP	EXPELC_DE	Export electricity_DE	PJ	PJ/a	DAYNITE
EXP	EXPELC_FR	Export electricity_FR	PJ	PJ/a	DAYNITE
EXP	EXPELC_IT	Export electricity_IT	PJ	PJ/a	DAYNITE
EXP	EXPLTH	Credit for heat from CHP	PJ	PJ/a	ANNUAL
IMP	IMPELC_AT	Electricity import_AT	PJ	PJ/a	DAYNITE
IMP	IMPELC_DE	Electricity import_DE	PJ	PJ/a	DAYNITE
IMP	IMPELC_FR	Electricity import_FR	PJ	PJ/a	DAYNITE
IMP	IMPELC_IT	Electricity import_IT	PJ	PJ/a	DAYNITE
IMP	IMPHCO	Import of coal	PJ	PJ/a	ANNUAL
IMP	IMPNGA	Natural Gas import	PJ	PJ/a	DAYNITE
IMP	IMPOIL	Import of Crude oil	PJ	PJ/a	DAYNITE
IMP	IMPURN	Uranium	PJ	PJ/a	ANNUAL
IMP	IMPURN_FBR	Uranium for the FBR	PJ	PJ/a	ANNUAL
RNW	RNWBIO	Biogas from waste	PJ	PJ/a	SEASON
RNW	RNWGEO	Very Deep geothermal resources	PJ	PJ/a	ANNUAL
RNW	RNWHYDD	Hydro (Dams)	PJ	PJ/a	DAYNITE
RNW	RNWHYDR	Hydro (Run of river)	PJ	PJ/a	SEASON
RNW	RNWSOL	Solar radiation	PJ	PJ/a	DAYNITE
RNW	RNWWIN	Wind resources	PJ	PJ/a	SEASON
RNW	RNWWOD	Wood biomass resource (waste)	PJ	PJ/a	ANNUAL
RNW	RNWWST	Wastes (industrial, Kehricht, …)	PJ	PJ/a	ANNUAL
STGTSS	PUMPSTG-TSS	Electricity storage in Dam hydro TSS	PJ	PJ/a	DAYNITE

CHP – Combined Heat and Power generation technology
ELE – Electricity generation technology
DSCINV – Lumpy investment technology
EXP – Export resource technology
IMP – Import resource technology
RNW – Renewable resource technology
STGTSS – Energy storage technology at time slice level

Appendix V: Swiss electricity trade balance

EXPORT (In GWh)															
	2008					2005					2000				
month	AT	DE	FR	IT	Total	AT	DE	FR	IT	Total	AT	DE	FR	IT	Total
Jan	0	59	301	2185	**2545**	12	34	255	2243	**2544**	3	321	274	1760	**2358**
Feb	0	55	182	2176	**2413**	0	38	327	2430	**2795**	4	297	109	1757	**2167**
Mar	0	73	240	2146	**2459**	0	68	268	2421	**2757**	4	342	115	1962	**2423**
Apr	0	88	165	1933	**2186**	0	75	129	2354	**2558**	4	359	84	1766	**2213**
May	3	334	116	2333	**2786**	147	150	82	2284	**2663**	42	754	87	1926	**2809**
Jun	18	520	266	1636	**2440**	0	104	237	2020	**2361**	31	784	61	1896	**2772**
Jul	10	509	391	2117	**3027**	0	186	327	2139	**2652**	16	381	68	1949	**2414**
Aug	0	323	346	1608	**2277**	34	286	90	1753	**2163**	39	493	110	1275	**1917**
Sep	68	449	552	1932	**3001**	4	218	179	1951	**2352**	18	250	287	1849	**2404**
Oct	2	128	463	1853	**2446**	0	155	80	2378	**2613**	28	330	255	2295	**2908**
Nov	5	109	164	2136	**2414**	14	145	186	1957	**2302**	17	396	129	1924	**2466**
Dec	0	62	362	2107	**2531**	0	114	477	1477	**2068**	8	443	73	1976	**2500**
	106	**2709**	**3548**	**24162**	**30525**	**211**	**1573**	**2637**	**25407**	**29828**	**214**	**5150**	**1652**	**22335**	**29351**

IMPORT (In GWh)															
month	AT	DE	FR	IT	Total	AT	DE	FR	IT	Total	AT	DE	FR	IT	Total
Jan	779	1915	983	6	**3683**	725	1864	951	0	**3540**	386	1252	881		**2519**
Feb	738	1603	1013	7	**3361**	821	1797	605	0	**3223**	417	1131	902		**2450**
Mar	838	1642	858	22	**3360**	905	1650	787	0	**3342**	384	1133	1025	1	**2543**
Apr	817	1228	794	13	**2852**	899	1811	820	0	**3530**	384	920	815		**2119**
May	627	562	727	9	**1925**	752	1184	914	6	**2856**	283	338	531	1	**1153**
Jun	339	471	540	62	**1412**	764	1135	804	7	**2710**	210	319	427	3	**959**
Jul	452	353	446	29	**1280**	730	1487	591	7	**2815**	290	698	682		**1670**
Aug	553	726	562	37	**1878**	516	1424	807	7	**2754**	250	658	705	2	**1615**
Sep	334	645	419	61	**1459**	606	1014	751	8	**2379**	424	952	684	3	**2063**
Oct	540	1520	665	86	**2811**	856	1313	1059	6	**3234**	411	825	721		**1957**
Nov	618	1450	840	26	**2934**	637	1523	1078	16	**3254**	334	823	858		**2015**
Dec	814	1743	940	42	**3539**	908	1872	807	74	**3661**	388	1052	1126		**2566**
	7449	**13858**	**8787**	**400**	**30494**	**9119**	**18074**	**9974**	**131**	**37298**	**4161**	**10101**	**9357**	**10**	**23629**

Appendix VI: Technical characterisation and costs of new technologies

Technology description	Vintage year	Lifetime	LF/AF	Capital Cost	Fixed O&M cost^	Variable O&M cost^	Decommissioning cost	Electrical efficiency	Construction time
		Years	*%*	*CHF/kW*	*CHF/kW*	*CHF/GJ*	*CHF/kW*	*%*	*Years*
Refurbishing existing river hydro	2011	80	52%	2870	18.2	1.7		80%	3
Refurbishing existing dam hydro	2011	80	25%	3500	9.7	1.8		80%	3
Refurbishing existing small hydro	2011	80	52%	2870	18.2	1.6		80%	3
New build river hydro	2015	80	63%	6560	18.2	1.7		80%	3
New build small hydro	2015	80	63%	8200	18.2	1.7		80%	3
New build dam hydro	2015	80	27%	10000	9.7	1.8		80%	5
Nuclear: Gen2 (LWR)	2020	50	91%	4250	23	3.3	606	32%	6
Nuclear: Gen3 (EPR)	2030	60	91%	4250	12	1.9	490	35%	6
Nuclear: Gen4 (FBR)	2050	40	90%	4750	55	0.2		40%	6
Coal (SCPC)	2020	30	80%	2350	40	0.7		43%	3
	2030	35	87%	2150	45	0.8		50%	3
	2050	35	87%	2050	45	0.8		54%	3
Coal (SCPC - post CCS)	2030	35	87%	3200	69	0.9		43%	3
	2050	35	87%	2900	69	0.9		49%	3
Natural Gas (GTCC) ##	2012	25	82%	1150	8	6.7	45	58%	3
	2030	25	82%	1050	8	6.7	40	63%	3
	2050	25	82%	1050	8	6.7	40	65%	3
Natural Gas (GTCC - post CCS)	2030	25	82%	1700	16	13.4	70	56%	3
	2050	25	82%	1500	16	13.4	60	61%	3
CHP: Biomass ICE	2012	15	86%	6000	180	10.3	161	36%	

Technology description	Vintage year	Lifetime	LF/AF	Capital Cost	Fixed O&M cost^	Variable O&M cost^	Decommis sioning cost	Electrical efficiency	Constructi on time
		Years	*%*	*CHF/kW*	*CHF/kW*	*CHF/GJ*	*CHF/kW*	*%*	*Years*
CHP: Biomass ICE	2030 2050	15 15	86% 86%	4200 3800	126 114	5.4 5.4	81 73	42% 44%	
CHP: Natural gas	2012 2030	20 20	51% 51%	2650 2100		9.7 6.9	133 105	32% 42%	
CHP: Wood gas	2012 2030	20 20	51% 51%	9682 4833		16.9 9.8	484 242	32% 42%	
CHP: Natural gas fuel cell	2012 2030	5 15	51% 51%	25000 3000		91.7 5.6	1250 150	40% 53%	
Solar PV	2010 2030 2050	40 40 35	11% 11% 11%	6500 2850 1950	5 5 5	0.6 0.6 0.6	250 85 45	100% 100% 100%	
Wind	2010 2030 2050	20 20 20	14% 14% 14%	2150 1750 1750	44 28 28	13.9 8.9 8.9		100% 100% 100%	
Geothermal	2020 2030	30 30	80% 80%	13825 6650	134 87	12.4 29.0	691 333	40% 40%	3 3
Waste incinerator	2020	30	15%	2350	40	0.7		43%	3
Pumped hydro storage	2030	80	27%	7000	10	2		80%	3
Refurbishing the existing pumped hydro storage	2011	80	27%	700	10	2		80%	3
Interconnectors	2015	50	100%*	458	1.2	0.4		80%	

^ In some technologies, fixed O&M cost are reflected in variable O&M cost and vice versa

* Subjected to fulfilling country specific market shares

These are base load plants. For flexible (merit order) plants, we used same cost assumption, but efficiency and availability factor are reduced by 20% to reflect erupted operation

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