Modeling Swedish Hydropower and Intermittent Production Variability in TIMES

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Abstract

This thesis considers the representation of intermittent and flexible power production in long-term energy system models, and more specifically at the Swedish hydropower's capability of balancing the variations from increased shares of power from intermittent energy sources. The thesis aims to investigate how a present national TIMES model can be improved to better capture the technical, physical, legal and market related restrictions controlling the flexibility of hydropower. The analysis is carried out in three steps. Firstly, a short literature review is conducted to describe the restrictions. Based on the review findings a TIMES-based model is thereafter developed. Finally, the model's calculations of the future energy systems optimal composition are compared to the ones of the conventional long-term energy system model TIMES-Sweden. The results indicate that models with lower temporal resolution overestimate the power system's ability to balance an increased share of power generation from intermittent sources due to the models' inability to account for the increased occurrences of situations with a high power demand and low intermittent production availability. They also highlight the importance of accounting for the power systems ability to balance unexpected production decreases due to forecast errors of intermittent production. When it comes to estimating the Swedish hydropower's flexibility the scope of the case study limits the number of conclusions than can be drawn. However, the results do indicate that the biggest challenges of balancing high shares of intermittent production with hydropower probably do not concern the hydropower system's ability to follow the increasing variability in residual load, but rather other limitations such as transmission capacities or restrictions stemming from production uncertainties.

Keywords

TIMES, Energy Flow Optimization Model, Dispatch Modeling, Hydropower, Wind Power, Intermittency, Variability, Balancing Production Variations, Hydro-Thermal System

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Contents

1 Introduction

1.1 Background

Long-term energy system models are tools for evaluating energy policies and comparing future technology pathways. The models make it possible to identify the most cost-effective combination of competing technology alternatives, while capturing complex interactions within the energy system and taking physical, technical and political restrictions into account. By enabling holistic studies of the energy system, the models can work as a complement to more detailed descriptions of costs and potentials. The Integrated MARKAL-EFOM System (TIMES) is a tool developed by the International Energy Agency's Energy Technology Systems Analysis Program (IEA-ETSAP) for generating such models. One TIMES-based model is TIMES-Sweden, which has been used on behalf of the Swedish environmental advisory committee (Miljömålsberedningen) to analyze different scenarios for achieving Swedish climate targets (Krook-Riekkola 2016).

TIMES-Sweden and other long-term energy system models usually depict entire energy systems and includes vast descriptions of technology options and demand sectors. To keep the models transparent and the results of the conducted studies possible to interpret a simpler description of the individual technologies and a low temporal resolution is usually beneficial or even necessary, and the representation of electricity dispatch is therefore often limited or left out entirely. Historically, this has not been a big issue since the power system has almost entirely consisted of dispatchable power sources. Lately, however, intermittent power production has expanded drastically, and as the transition to renewable energy continues an increasingly large share of the generated power will most likely come from intermittent sources. As the electricity system evolves, and the importance of effective output increases in relation to the amount of energy produced there is a risk that these simple descriptions of the electricity system will not be sufficient. This might lead to the neglecting of the importance of certain future technologies, such as energy storage, or the under- or over estimations of the potentials of others. An important task for energy system modelers is therefore to develop models or methods to adequately describe power systems with high shares of intermittent production.

For energy systems similar to Sweden's, the high share of hydropower constitutes a big opportunity for balancing an increased share of intermittent production. Hydropower and the technical, physical, legal and market related restrictions controlling its flexibility therefore play a significant role when assessing future developments of such systems. In TIMES-Sweden, hydropower is described by two categories corresponding to hydropower plants with and without storage capacity respectively. Within each category all plants are aggregated and the production is assumed to vary according to how it has been regulated historically. In a future with high shares of intermittent power production the hydropower might be used differently, and a representation based on historical values might not describe the system accurately.

1.2 Aim

This thesis considers the representation of intermittent and flexible power production in long-term energy system models. The purpose is to explore the extent to which Swedish hydropower can be used to balance production variations and how its flexibility impacts the prospects of incorporating large shares of intermittent generation into the power system.

The thesis aims to investigate how a present national TIMES model can be improved to better capture the technical, physical, legal and market related restrictions of hydropower. The analysis is carried out by answering the following research questions:

1. How are the technical, physical, legal and market related restrictions impacting hydropower's ability to balance production variations?
2. How can a TIMES-based model be developed in which these restrictions are accounted for?
3. How does the developed model's calculations of capacity investments, allocation of power production and hydropower utilization differ from the ones of a conventional model such as TIMES-Sweden?

1.3 Method

The research questions are answered in three steps. First, a short literature review is conducted in order to describe the technical, physical, legal and market related restrictions that control hydropower production and how these affect its ability to balance variations from an increased amount of power from intermittent sources. The review also contains a description of how Nordic hydropower is described in existing models. This provides an insight into how hydropower is modeled and what restrictions others have seen as significant to include on different modeling levels.

Based on the findings from the review a TIMES-based model is thereafter developed. The model is restricted to the hydropower of the Lule-river. Furthermore, it focuses solely on the power sector and only includes a limited number of generation technologies.

Finally, the model's calculations of capacity investments, allocation of power production and hydropower utilization are compared to the ones of TIMES-Sweden. To perform the comparisons, a new model is constructed which mimics the implementation of hydropower in TIMES-Sweden but only contains the chosen technologies

1.4 Limitations

A number of limitations have been made in order to achieve the aim of this thesis with limited time and resources. The most significant of these are listed below. A more detailed description of the limitations can be found in the model description, and a discussion about their effects is carried out in chapter 7. Discussion.

- The developed model is restricted to the hydropower of the Lule River. The hydropower of the Lule River constitutes around 25% of the total installed hydropower capacity in Sweden and its production amounts to ca. 20-25% of Sweden's annual hydropower production.
- The model is also restricted to focus solely on the power sector and only includes a limited number of generation technologies. The included technologies are chosen to represent base load, flexible and peak generation in the Swedish power sector.
- Furthermore, the study focuses on hydropower's flexibility to balance variations within the year. This means that the yearly variations in intermittent and hydropower production and the reservoirs' ability of storing energy over several years are not attended to.

1.5 Disposition

The report is structured in the following manner. Firstly, Chapter 2 provides a short introduction to energy system models generally and TIMES and TIMES-Sweden specifically. Chapter 3 contains the literature review of the technical, physical, legal and market related restrictions that control hydropower production and how these affect its ability to balance variations from an increased amount of power from intermittent sources. Thereafter, the developed model is presented in chapter 4.

Chapter 5 contains a description of the comparative model and the case study for which the models are applied, and chapter 6 contains an analysis of the model results. Finally, the developed model and results of the case study are discussed in chapter 7 and the conclusions summarized in chapter 8.

2 Energy System Modeling

This chapter provides a short introduction to some of the theoretical concepts that are important when approaching energy problems through system models. It also presents descriptions of the applied model tool, TIMES, and the national model TIMES-Sweden, from which the problem formulation of this thesis originates.

2.1 Energy System Modeling

2.1.1 Systems Analysis

The accommodation of energy services is accomplished through several steps of extraction, conversion and transportation of energy commodities. To provide a certain service, e.g. space heating, several of these processes are combined and the contribution from each process depends on:

- the availability of the process itself,
- the availability of the connected processes,
- the demand of the energy service, and
- the competitiveness of the competing technologies.

The interactions between energy processes and demands constitute a system and only by approaching it as one is it possible to compare different pathways and find the most beneficial substitutions between the different technology options. A both useful and necessary method when studying energy problems is therefore systems analysis. The basis of this approach is described below.

In *The Systems Approach* C. West Churchman outlines five basic considerations for thinking about the meaning of a system (Churchman 1968: 29-30):

1. the total system objectives and, more specifically, the performance measures of the whole system,
2. the system's environment: the fixed constraints,
3. the resources of the system,
4. the components of the system, their activities, goals and measures of performance, and
5. the management of the system.

For energy systems, one way of identifying some of the considerations above is by making a reference energy system (RES). A RES illustrates all the technology pathways which are associated with a specific demand, and contains all flows and processes from source to final use (Tosato 2009). A simplified example of a RES for space heating from gas is shown in figure 1.

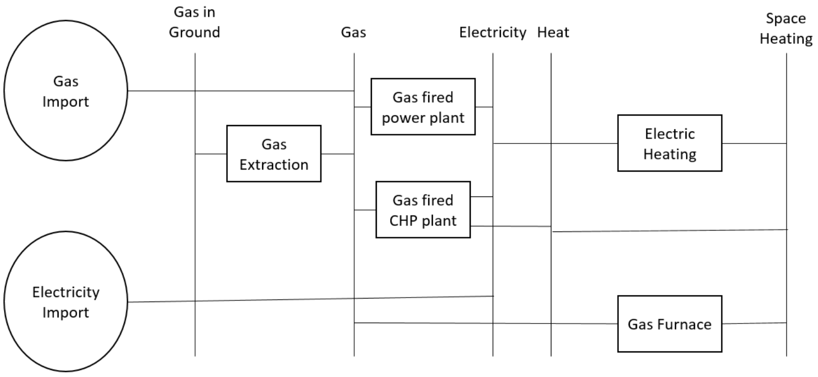

Figure 1: Example of a reference energy system.

In the figure, the vertical lines represent the *resources* of the system. The resources are the assets that are used by the system to perform its actions and are the objects that can be restructured in order to achieve the system's goals (Churchman 1968: 42). For energy systems, the resources are made up of different types of commodities that are present in the energy provision chain. The two most important commodity types are perhaps energy carriers (e.g. gas, biomass, electricity) and demands, but commodities may also consist of materials (e.g. steel, iron), emissions and financial resources.

The square boxes represent the *components* of the system. These are the parts of the system that perform the system's actions (Churchman 1968: 43). For energy systems, the components are made up of the extraction, conversion and transportation processes in the energy provision chain.

The circles represent the system's *environment*. The environment is considered to be what lies outside the system and consists of the objects that from the system's perspective can be regarded as ”fixed” or ”given” (Churchman 1968: 39-40). According to Churchman, something should be considered to belong to the environment if it influences the system's goals but cannot itself be influenced by the system. In reality this definition is floating and the choice of what is inside and outside the system is also affected by practical considerations. A RES illustrates elements of the environment associated with commodity flows. In addition to these, there are several factors of the environment that are not included, such as laws and other social and political restrictions.

The *objectives* and *management* of the system are not included in the RES and have to be identified elsewhere. The management is according to Churchman responsible for the shaping of the system's plans: it sets the goals for the components, distributes the resources and decides the performance of the system (CH: 47). If the objectives are the system's goals, the environment the given conditions and the resources and components the building blocks, the management represents *how to get there*. How the management is designed varies depending on the system's objectives and may consist of control measures, investment schemes or operation schedules.

2.1.2 System Models

As the level of detail increases and more commodities and demands are included the energy systems can get very complex and difficult to handle mentally. This is where mathematical models and computer simulations can be useful or even necessary. Churchman describes models as tools for enhancing the human thought processes. While the systems analyst controls all the basic conditions the models can be used to derive the more wide-ranging and complicated consequences (Churchman 1968: 61).

This is a distinction that is important to keep in mind. Rather than, like traditional engineering models, providing one correct answer, energy system models are abstract and often simplified descriptions of the real world. The models can, however, be useful as they are able to take more variables into account. Furthermore, working with models can serve as a structured and systematic method for approaching energy systems. According to the senior energy system analyst Giancarlo Tosato, mathematical models are often preferred over informal mental models since decision-makers request (Tosato 2009):

- quantitative answers,
- reliable and established methods,
- transparent assumptions on framework, structure and data,
- internal consistency,
- regular updates when new relevant information is available,
- reproducible mental experiments, and
- iterations with new assumptions, towards new targets and for new policies.

2.1.3 Types of Energy System Models

Models describing energy systems can look very different depending on the objectives of the analyst. In order to clarify differences between models and straighten out the different fields of application it can be useful to divide the models into categories. In her disputation, Lisa Göransson makes a distinction between optimization (normative) models and simulation (descriptive) models (Göransson 2014). This thesis, and the theoretical concepts described above, focuses on the former, i.e. normative models in which a system is optimized after what is regarded desirable. In contrast, simulation models try to reflect a behavior that is typically derived from statistical evaluations.

Göransson presents five different types of models, of which three are typically categorized as optimization models: investment models, dispatch models and unit commitment models. Dispatch models and unit commitment models minimize the operational costs of an energy system. Unit commitment models can be seen as a subtype of dispatch models, in which units are described individually with specific properties. By minimizing the operational costs, the models investigate how to deploy a specific set of energy technologies at the lowest cost.

The models applied in this thesis are investment models. Investment models differ from dispatch models and unit commitment models in that they take investments in new production capacity into account. In addition to describing how the energy system is optimally operated, the models thus calculate how the system may expand at the lowest cost. Therefore, investment models typically optimize the energy system over longer time periods. Investment models also typically contain simpler descriptions of individual technologies and usually have a lower temporal resolution, since the complexity accompanying the inclusion of capacity investments and the longer time periods otherwise would make the computation time long and the results difficult to interpret.

2.2 TIMES

The Integrated MARKAL-EFOM System (TIMES) is a tool developed by the International Energy Agency's Energy Technology Systems Analysis Program (IEA-ETSAP) for generating energy system investment models. IEA-ETSAP describes TIMES as a technology rich, bottom-up model generator, which uses linear-programming to produce a least-cost energy system, optimized according to a number of user constraints, over medium to long-term time horizons (IEA ETSAP 2017). Furthermore, the models can be characterized as dynamic and having perfect foresight, since they optimize across entire time horizons and all investment and operational decisions are made with full knowledge of future events. TIMES is usually applied to the analysis of the entire energy sector, but may also be applied to study single sectors such as the electricity and district heat sector (Loulou et al. 2016).

The generated models attempt to solve and determine the energy system that meets the energy service demands over the entire time horizon at the lowest cost. The outputs consist of information about the optimal system at each time period, such as capacity investments, energy flows, greenhousegas emissions, energy commodity prices and marginal abatement costs. In addition to constraints controlling technical and physical properties, the system may be optimized under various constraints representing political goals (e.g. emission reduction or renewable electricity penetration targets) or regulations (e.g. carbon emission tax) (IEA ETSAP 2017).

2.2.1 Basic Structure

The basic model structure of a TIMES model can be understood as a RES similar to the one shown in figure 1 above. All TIMES models are constructed from three basic entities: commodities, processes and commodity flows (IEA-ETSAP 2017). The commodities and processes are defined as in the RES of figure 1, with the only difference that in TIMES, processes are also used to describe the system's environment. The remaining entity, commodity flows, describes the links between commodities and processes and represent the inputs or outputs of the different processes. To construct a TIMES model these entities have to be defined and together they make up the system. When defining this system, process/commodity data are specified to describe the individual characteristics of each process/commodity. This may for instance include defining production efficiencies, installed capacity, costs and availability factors for energy production processes, or defining demand curves for energy demands.

When processes, commodities and commodity flows have been defined, TIMES uses the information to create a linear equation system whose objective is to minimize the energy system's total costs. From the definitions of commodities, processes and commodity flows, linear constraints are formulated which describe the relationships between the different entities and the specified characteristics of individual processes/commodities. These constraints govern the dynamics of the system and enforce most of its technical and physical properties. In addition to these it is possible to include so called user constraints. User constraints can be implemented to describe more advanced properties or constraints which restrict the behavior of a group of entities or entities at different time levels. The structure of TIMES thus provide a structured method to define a large number of interconnected processes and commodities by specifying parameters for individual entities, while at the same time enabling modeling liberty through user constraints.

2.2.2 Temporal Resolution

In TIMES the time horizon and temporal resolution are defined by the user. As stated, however, TIMES is designed to perform optimizations over medium to long term time horizons and its structure and functions are therefore formed accordingly.

The temporal representation is described by time-periods and time-slices. The time horizon is divided into a user-chosen number of time-periods, each period containing a (possibly different) number of years. Except for the cost objective function, which differentiates between payments in each year of a period, each year in a given period is considered identical, and any other input or output related to the period applies to each year. All years within a period can therefore be represented by one year, the so called milestone year (Loulou et al. 2016a). The milestone years also constitute points in time where decisions may be taken by the model, e.g. installations of new capacity or changes in the energy flows (Loulou et al. 2016b).

To capture that the processes and commodities might have different characteristics depending on the time of year there are also time divisions within a year, called time-slices. Time-slices can be specified on a seasonal, weekly and daily level and can be arranged subsequently to form a time-slice tree (Loulou et al. 2016a). An example of a time-slice tree can be seen in figure 2, which shows a schematic illustration of the temporal representation of TIMES.

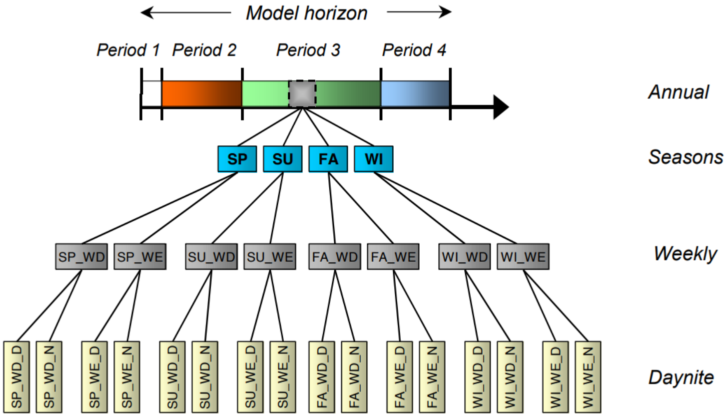

Figure 2: A schematic illustration of the temporal representation of TIMES. Source: (Loulou et al. 2016a).

As can be seen in figure 2, the time-slices usually do not represent a specific point in time but rather a group of time points, e.g. an average summer weekday. This has the consequence that the temporal representation, unlike models over shorter time horizons, usually is non-linear.

2.2.3 Peaking Constraint

Most TIMES models have a low temporal resolution. To insure against possible production or commodity shortfall due to uncertainties (e.g. low wind availability), unplanned equipment down time and random peak demand that exceeds the average, a peaking constraint is often included (Loulou et al. 2016a). In its most simple form, the peaking constraint for a specific commodity, c, and time-slice, ts, can be formulated as:

$$(1+COM\_PKRSV[c,ts]) \times demand[c,ts] \leq \sum_{p \in P(c)} PF[p,ts] \times cap(p,c,ts) \quad (1)$$

where $demand$ represents the demand of commodity c at time-slice ts (including the consumption of c from other processes), P the group of all processes producing c and cap the installed capacity of process p at ts. COM_PKRSV is the reserve coefficient, which is the percentage by which the average demand in time-slice ts should be increased to represent the actual peak load. PF specifies the fraction of technology p's capacity that is allowed to contribute to meet the peak load. For predictable power sources, PF is usually set to be equal to the availability factor[1] or 1 (depending on how the COM_PKRSV for electricity has been defined), while intermittent power sources usually have a low PF, either representing worst cases (e.g wind $PF = 0$) or average availabilities (e.g. wind $PF = 0.3$).

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[1] As defined in section 2.3.1

2.3 TIMES-Sweden

TIMES-Sweden is a TIMES-based energy system investment model initially developed as a part of the Pan European TIMES model (PAN) and has thereafter been further developed to capture Swedish conditions (Krook-Riekkola 2015). The model has been used on behalf of the Swedish environmental advisory committee to analyze different scenarios for achieving Swedish climate targets (Krook-Riekkola 2016).

Figure 3 shows an illustration of TIMES-Sweden. In the model, the energy system is represented by 7 sectors: industries, residential, services, agriculture, transports, electricity & district heating and energy supply and fuel production. The model is driven by a given demand which either is represented by useful energy (PJ/year) or by services or commodities (pers km/year, ton/year, etc) (Krook-Riekkola 2016). Optimizations are carried out with time horizons of typically 20-50 years. Each year is divided into 12 time-slices that represent an average of day, night and peak demand for every one of the four seasons of the year (e.g. summer day, summer night and summer peak, etc.).

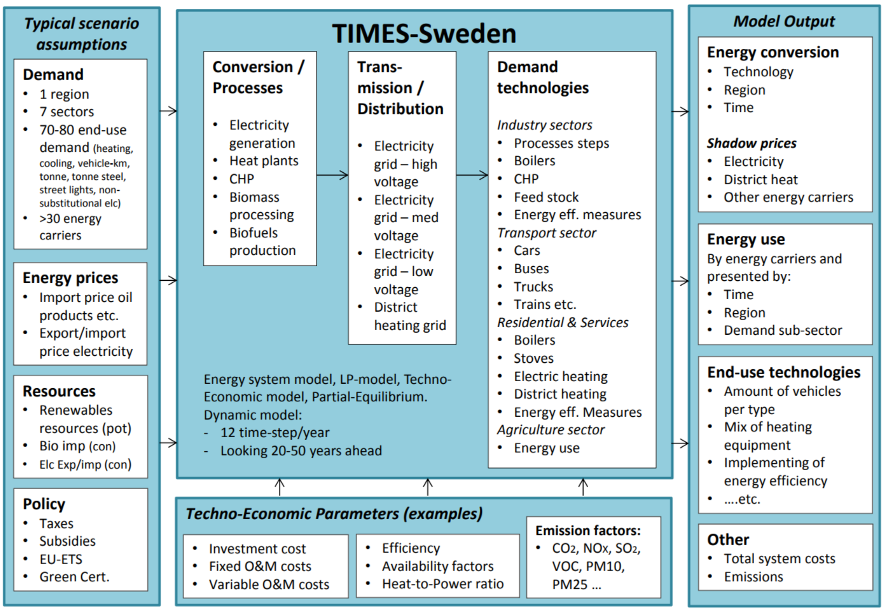

Figure 3: Illustrative description of TIMES-Sweden. Source: (Krook-Riekkola 2015).

2.3.1 Representation of Hydropower

In TIMES-Sweden, hydropower is described by two processes corresponding to hydropower plants that are easily regulated and plants that have limited reservoirs. Within each category all plants are aggregated. The hydropower production in each time-slice is decided from its production costs, installed capacity and availability factors. In TIMES, the availability factors are based on historical data and indicate the percentage of a process's installed capacity which is functional in each time-slice or, put another way, the percentage of the time-slice in which the process is functional[2]. Together with the installed capacity the availability factors thus set an upper limit to how much energy that can be produced within a specific time-slice. Availability factors can be defined at any level of the time-slice tree.

Table 1 shows TIMES-Sweden's assumptions regarding installed capacity and availability factors for the two hydropower processes. The installed hydropower capacity is considered to remain throughout the entire time horizon. In addition, there is a possibility to invest in a limited amount of new hydropower capacity.

Table 1: Installed capacity and availability factors (AF) for the two hydropower processes in TIMES-Sweden. The two letter notations, RD, SP, WN, etc. describe individual time-slices. The first letter corresponds to season (R for spring, S for summer, F for fall and W for winter) and the second letter to time of day (D for day-time, N for night-time and P for peak hour).

Process		Easily Regulated	Modest Regulated
Installed Capacity	GW	8.25	8.25
AF-Annually	%	0.65	0.43
AF-RD	%	0.68	0.45
AF-RN	%	0.68	0.45
AF-RP	%	0.68	0.45
AF-SD	%	0.68	0.43
AF-SN	%	0.68	0.43
AF-SP	%	0.68	0.43
AF-FD	%	0.68	0.45
AF-FN	%	0.68	0.45
AF-FP	%	0.68	0.45
AF-WD	%	0.68	0.55
AF-WN	%	0.68	0.55
AF-WP	%	0.68	0.55

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[2] I.e: Availability Factor = $\frac{\text{Maximum Production}}{\text{Installed Capacity} \times \text{Hours}}$

3 Hydropower Modeling

This chapter contains a short literature review which is conducted to describe the technical, physical, legal and market related restrictions that control hydropower production and how these affect its ability to balance variations from an increased share of intermittent production. Firstly, the restrictions are presented and divided into the four categories mentioned above, and the challenges of intermittent production are described generally. The information presented in these sections is based on two reports focusing on these issues: (Bruce et al. 2016) and (Stoll et al. 2017). Thereafter, the review contains a description of four models modeling Nordic hydropower and how the challenges of intermittent production are tackled in these models.

3.1 Restrictions

There are several restrictions governing the production of hydropower systems. These restrictions can be categorized as technical, physical, legal and market related. The four categories are described below.

3.1.1 Technical

Technical restrictions concern the transformation from water to electricity in hydropower plants, of which maybe the most important are related to the efficiency and available capacity. In a hydropower plant, the power generation is determined by the head, the water flow and the efficiency of the plant's aggregate. The efficiency of the aggregate depends on the water flow through a non-linear relationship which differs between aggregate types and individual aggregates. While the maximal aggregate efficiency is typically above 90 % the efficiency at maximal water flow is thus lower, somewhere around 80 % (Bruce et al. 2016). Furthermore, there are certain water flow intervals in which operation increases wear and tear, shortens the lifetime of equipment, and can negatively impact performance. Although it is not a strict requirement, operation within these rough zones is strongly discouraged by operators (Stoll et al. 2017).

3.1.2 Physical

There are also purely physical restrictions related to hydrological conditions and physical properties of the water systems. Primarily, these restrictions control the available energy by imposing constraints on water supply. The amount of water in a reservoir is determined by inflows, outflows and losses through evaporation and seepage. The inflows consist of water from upstream and natural inflows from minor streams, precipitation and deglaciation, and the outflows consist of water to downstream hydropower plants. For a river system, the production is principally restricted by the natural inflow, which can vary largely from year to year. In exploited rivers there are usually several hydropower plants upstream and downstream. In such systems, the water supply of a plant also depends on the activity of the plants upstream.

The hydrological coupling between plants mainly affects the amount of water spill (Bruce et al. 2016). In a river where all aggregates are turned on simultaneously, all the reservoirs where the maximum turbine water flow downstream is bigger than the maximum turbine water flow upstream will start to empty and vice versa. To keep the reservoirs' water levels at permitted intervals water would in this case have to be spilled to reservoirs with decreasing water levels or spilled from reservoirs with increasing water levels. To limit the amount of water spill (and consequently spill of energy) the activity of the plants thus have to be coordinated.

Other physical restrictions concern the sizes of reservoirs, streams and spillways. However, these quantities often have rather small impacts, since there usually exist more strict, legal restrictions (Amelin et al. 2009). Ice-conditions and maritime traffic may also impose practical restrictions on how a hydropower system is operated. For example, it is important to have (steady) flows during ice freeze-up, since ice could otherwise detach and cause damage to the plants (Bruce et al. 2016).

3.1.3 Legal

The production is also limited by legal restrictions in terms of water usage regulations. Water usage regulations contain ecological considerations and are enforced to reduce hydropower's impact on the local environment (Bruce et al. 2016). These regulations place restrictions on hydropower operation, including limitations on the minimum amount of water that must be released, reservoir level restrictions, and flow rate requirements (Stoll et al. 2017). In many cases, the legal restrictions place tougher constraints on the flexibility of hydropower than technical and physical conditions such as water supply, reservoir size and spillways (Bruce et al. 2016).

3.1.4 Market Related

The last category of restrictions is market related restrictions. These include requirements imposed on hydropower plants as a consequence of participating in energy or ancillary service markets of the power system. Primarily, participation requires following any commitment or dispatch schedules created by these markets (Stoll et al. 2017).

In Sweden, there exist several ancillary service markets to handle variations of the residual load. In these markets, power producers offer to withhold capacity so that, if needed, power generation can quickly increase or decrease. For hydropower facilities participating in such markets, this places upper and lower limits on the amount of installed capacity that can be utilized at any one time (Bruce et al. 2016).

Other market related restrictions concern production planning. In reality, hydropower producers deliver production bids to the energy market in advance. The bids are based on operational models and electricity price prognoses. In theory this leads to optimal utilization of water resources since the electricity price reflects the electricity need (Bruce et al. 2016). If the prognoses are incorrect, however, this is not true. In a future power system with more intermittent production the size and frequency of prognosis errors will probably increase, which might lead to a less optimal utilization of water resources.

3.2 Balancing Intermittent Production

3.2.1 Balancing Variations in Residual Load

The power system requires balance between consumption and production, momentarily as well as over longer time periods. Non-predictable consumption and production have to be balanced by predictable consumption and production. The residual load, P_{res}, describes the amount of effective output that has to be provided by predictable power production, and is defined as (Bruce et al. 2016):

$$P_{res} = P_{load} - P_{np} \tag{2}$$

where P_{load} denotes electricity consumption and P_{np} the power production from non-predictable energy sources.

An increase of intermittent power production will affect the residual load at all time levels from seconds to years. The production from intermittent sources such as wind and solar variates between zero and installed capacity and the fluctuations have varying durability, ranging from seconds to several days in the case of wind (Bruce et al. 2016). As a consequence, the operational patterns of predictable production facilities will have to adapt to balance these variations. Seasonal patterns also change according to the seasonal availabilities of intermittent production. For example, power systems with high shares of solar power need more predictable power to be available during the winter season.

In Sweden, hydropower is used to balance the majority of the variations in residual load. According to calculations by (Bruce et al. 2016), between 2012 and 2014, hydropower balanced on average 102 % [3] of the variations in residual load within the day, 69 % of the variations between days and 46 % of the variations between seasons. Hydropower and its capability of balancing new fluctuations in residual load thus play an important role regarding the integration of intermittent production and the question of how much that can be integrated in the future power system. This capability in turn depends on the restrictions formulated above. For seasonal variations, the capability is primarily affected by the sizes of energy storage reservoirs (including any restrictions imposed by water usage regulations). The capability of balancing variations within and between days is rather restricted by how fast the hydropower systems can switch between production levels, available capacities and to what extent the systems are able to operate at maximal production levels during longer time periods. According to (Bruce et al. 2016), any limitations on how much intermittent power production that can be balanced by Swedish hydropower does probably not concern the sizes of reservoirs, but rather the available capacity of the plants, the flexibility of the river systems and the transmission capacity of the power grid.

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[3] That the percentage is over 100 % means that Sweden during the period exported some of its production balancing.

3.2.2 Forecast Uncertainty

In addition to an increase in residual load variations, intermittent power production also creates challenges due to the difficulty of correctly predicting its production. Primarily, this increases the amount of available production capacity and energy resources needed to balance unexpected increases and decreases in residual load. Today, Swedish hydropower is used to balance almost all unexpected increases and decreases within and between hours (Bruce et al. 2016). As mentioned in section 3.1.4, this places extra restrictions on how a hydropower facility is operated since it must always be able to quickly increase or decrease its production. The difficulty of correctly forecasting intermittent production may lead to an increase of these margins of operation. According to (Bruce et al. 2016), these restrictions will primarily affect the availability of production capacity rather than water resources, since the errors in predicted energy amounts are estimated to be small compared to the energy stored in reservoirs and water in the worst case can be spilled upstream to provide water resources for plants downstream.

As also mentioned in section 3.1.4, the difficulty of correctly predicting intermittent production also complicates optimal utilization of water resources. This has an effect both on shorter and longer time frames, since short-term prognoses determine the electricity price and long-term forecasts determine the value of the water in the reservoirs.

3.3 Existing Models Describing Nordic Hydropower

In order to provide a further insight into how hydropower is modeled and what restrictions others have seen as significant to include on different modeling levels, this section consists of a review of four existing models focusing on Nordic Hydropower. The first three included models have been used to investigate the hydropower's ability to balance variations from increased shares of intermittent production. The fourth model included in the review is TIMES-Norway, which is a TIMES based model of the energy system of Norway, whose power production to 95-99 % is made up of hydropower.

3.3.1 Short-term Optimization of Hydropower Production in the North of Sweden

In ELFORSK report 09:88, *Balansering av vindkraft och vattenkraft i norra Sverige* (Amelin et al. 2009), the regulating capability of the hydropower in the north of Sweden is investigated at various levels of wind power deployment, ranging from 1 000 to 12 000 MW. To be able to simulate the interactions between hydropower, wind power and other power generation technologies, and in a detailed manner take into account hydrological coupling and other physical, technical and legal restrictions, a model is developed.

Hydropower is modelled as a linear optimization problem, whose objective is to maximize the hydropower production during one week. Mathematically the optimization problem is formulated as:

$$\max\ Z = \sum_{i,t} H_{i,t} \tag{3}$$

where $H_{i,t}$ is the produced electricity in power plant i during hour t. The market is described by the linear constraint:

$$\forall\ t:\ \sum_{i} H_{i,t} + W_t + G_t \leq D_t + P \tag{4}$$

where W_t, G_t and D_t describe wind power production, thermal power production and consumption respectively, and are given as exogenous time series. P is the maximal transmission capacity from the area and limits the amount of exported electricity. Neighboring areas are assumed to take in all electricity that can be exported. Since no predictable capacity is removed, the power system is assumed to be able to handle all demands and the model thus only places a restriction on maximal production.

The high temporal and spatial resolution of the model makes it possible to include many of the restrictions discussed above. The model accounts for hydrological coupling, natural inflows and flow time between individual plants, and water usage regulations concerning reservoir levels, flow rates, ramping rates and daily differences in reservoir water levels. In some cases, the model also accounts for forbidden production levels and additional costs for start-up and ramping. To be able to describe efficiencies by linear functions, the dependence of the head is neglected and the power production is approximated as a function of the water flow. The efficiency is thus described by production factors (i.e. energy produced per water flow) at different production levels. To account for prognosis uncertainty, some weeks are simulated with a stochastic version of the model. This is done by reformulating equations (3) and (4), so that the objective is to maximize the expected production for three different wind production scenarios.

Spatial Scope and Resolution
The model describes hydropower generation in Sweden's price zone 1 and 2, and includes all hydropower plants that have an installed effect above 10 MW. In total, 154 plants are included with an aggregate effect of 13,2 GW, which represents approximately 80 % of the installed effect hydropower in Sweden. For hydropower, the spatial resolution is high, with physical, technical and legal restrictions being defined for each plant and hydrological coupling between different plants being taken into account.

Temporal Scope and Resolution
The model optimizes production over one week with a time granularity of one hour. Because of the rather high resolution, the hydropower capability to balance intermittent production can be investigated down to just above an intra-hour level. However, to be able to run the model, initial and terminal reservoir volumes for each plant have to be given exogenously (to prevent the hydropower plants from utilizing all water in the reservoirs during one week). The model can therefore provide a good description of how variations can be optimally handled by hydropower during one week, but not how water can be saved in reservoirs for longer periods.

Technology Representation
The model describes the electricity system only, and focuses on hydropower. Production from other power generating technologies is described by exogenously given time series, and is limited to production from wind and thermal power plants. Furthermore, no electricity storage or demand side management (DSM) technologies are included in the model. Since it is given exogenously, it is not possible to reduce or increase thermal power production in response to high or low wind production, and all balancing is done by hydropower.

3.3.2 A General Description of the Hydropower Capability to Balance a Large Share of Intermittent Power Production in Sweden

In a Master's thesis by Fredrik Obel (Obel 2012) the previously described model is expanded to include the whole of Sweden. The extended model is also used by Lennart Söder in the report *På väg mot en elförsörjning baserad på enbart förnybar el i Sverige, Version 3.0* (Söder 2013) to investigate if the hydropower is capable of balancing variations according to the calculations of desired hydropower that Söder has derived from statistical data. By combining simple calculations for longer time periods (1 year) and more detailed simulations for shorter time periods (1 week), Söder provides a broad description of the balancing of an electricity system with a large share of intermittent production.

In the report, several simulations are carried out for different scenarios. This section describes the method of part 3 of the report, which combines simple and detailed simulations of the Swedish electricity system in a scenario where nuclear power is phased out and all electricity in Sweden is delivered from renewable energy sources. The simulation is carried out in two steps. First, a preliminary assessment of the production from each energy technology is obtained. For every hour of the year, the electricity consumption and thermal, wind and solar production are determined from exogenously given time series. The hydropower production is thereafter calculated by:

$$\text{Hydropower} = \text{Electricity Consumption} - \text{Other Production} \tag{5}$$

combined with the extra constraint that the hydropower production at every moment has to remain between 1875 MW and 12 951 MW. If production exceeds consumption, thermal power production is assumed to be able to decrease down to 25 % of the initial production level. Moreover, the share of intermittent production is limited to 75 %.

After a preliminary assessment has been obtained, selected weeks are simulated with a more detailed model to investigate if the derived hydropower production is possible with regard to physical, technical and legal constraints. The model is a modified version of the one in (Amelin et al. 2009), that covers the whole of Sweden and where the problem is reformulated in order to obtain a feasible production which resembles the originally derived production as closely as possible. A deviation between the production levels is defined as an extra need of export or import, and the problem is formulated as the minimization of the extra need of export and import and the energy loss from spilling hydro energy. Mathematically, the objective function is formulated as:

$$\min Z = \sum_{i,t} (S_{i,t} + 0.8 * Exp_t + Imp_t) \tag{6}$$

where $S_{i,t}$ is the hydropower spill from plant i at hour t and Exp_t and Imp_t is the amount of extra export and import respectively. To encourage export ahead of spilling energy Exp_t is multiplied by the factor 0.8.

The detailed simulations include the same restrictions as the ones explained above for (Amelin et al. 2009). The preliminary assessment carried out for the entire year, however, only describes hydropower production through installed capacity and minimal and maximal production levels, which are based on historical data.

Spatial Scope and Resolution
The model describes the balance between electricity consumption and hydro, thermal, wind and solar power production in Sweden. The consumption and production are given as aggregated values for the whole of Sweden, and there are thus no restrictions on transmission capacity between different regions. In the detailed model, physical, technical and legal restrictions are described for each hydropower plant individually.

Temporal Scope and Resolution
The time granularity is one hour. As for time horizon, it differs between one week for the rough simulation and one hour for the detailed. The rough simulation provides an overview over the hydropower capability to balance a large share of intermittent production during different seasons and weather conditions. However, it should be noted that the amount of water in reservoirs is not calculated, and as in (Amelin et al. 2009) the amount of available water for the detailed simulations is given by historical data. This means that the possibility to store water between seasons is not investigated in detail.

Technology Representation
The model describes the electricity sector, and only includes consumption and production from hydro, thermal, wind and solar energy plants. Except for hydropower, whose production rate is calculated from the other power generating technologies, the production from thermal plants is able to decrease if the production exceeds the consumption. Otherwise, consumption and production rates are given by exogenous time series.

3.3.3 Short-Term Modeling of Hydropower in the Lule-River Regarding Operational Patterns and Concerns

Since 2006 the Swedish power company Vattenfall has been financing the research program Flexibel kraft (flexible power), whose goal is to clarify how hydropower should be adjusted to fit future demands. One area that has been studied extensively within the program is the expected hydropower production patterns in varying future scenarios. In a Master's thesis, made for Vattenfall, Joakim Lönnberg (2014) uses their hydropower model for operational planning, HOTSHOT, to develop an extended model that examines operational patterns for hydropower in Lule River when the wind power production is large.

In figure 4 the model is illustrated schematically. Every day HOTSHOT is provided with a forecast of the spot price of electricity for seven days ahead, together with the total amount of available water for optimization. From the provided information HOTSHOT calculates the optimal water utilization for the hydropower plants in the river, after which the procedure is repeated for 21 days. In contrast to the model in (Amelin et al. 2009) the model is not dynamic, since the optimal solution is found for one day at a time.

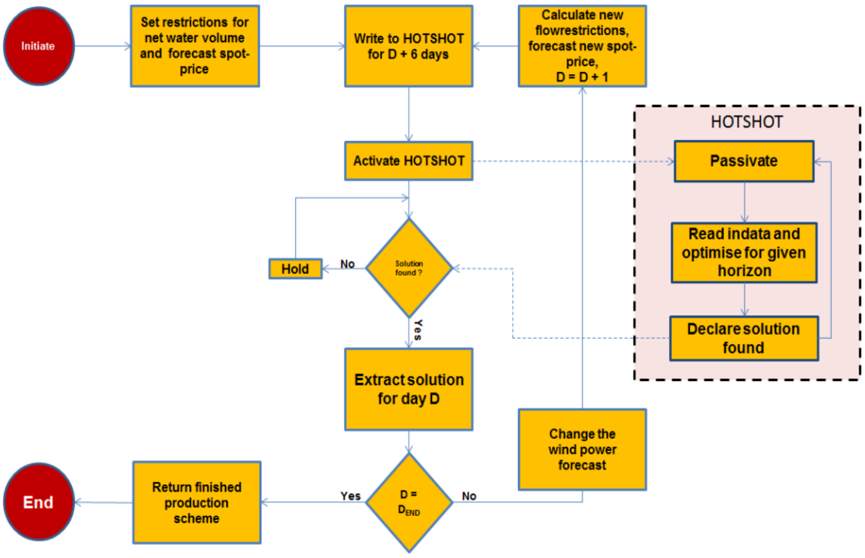


Figure 4: A schematic illustration of the model used by Lönnberg (2014). Source: (Lönnberg 2014).

HOTSHOT maximizes the revenue from the hydropower plants. The optimization problem is formulated as:

$$\max Z = \sum_{i,t} (s_t * H_{i,t} + vv_t * V_{i,t} - c_{ss}) \tag{7}$$

where $H_{i,t}$ is the produced energy by plant i during hour t, $V_{i,t}$ is the amount of available water at plant i during hour t, s_t is the spot price, vv_t is the water value and c_{ss} is the starting cost of a generator. c_{ss} is included in the objective function to limit the amount of starts and stops in the plants. The water value is a reference price of the water in a reservoir set by the producer and introduces the value of saving water.

HOTSHOT includes technical, physical and legal restrictions limiting reservoirs levels, flow rates and maximal and minimal effective output of the plants. The model accounts for hydrological coupling, natural inflow and flow times between individual plants. Furthermore, the efficiencies of the plants depend on both flow rate and the head, and start-up costs are included in the objective function.

Wind and thermal power production and electricity consumption affect the outcome by being input data to the spot price model, which makes the spot price forecasts. To represent prognosis uncertainty, the spot price model is provided with slightly inaccurate wind power time series, with randomly distributed errors that grow linearly from 6 % at day two to 10 % at day seven. This results in HOTSHOT being provided with a false spot price forecast, which causes problems with the optimal dispatching of water.

Spatial Scope and Resolution
The model describes the hydropower plants in the Lule river. HOTSHOT is used for operational planning at Vattenfall and includes a detailed description of the power plants. Electricity consumption and other production are given for the whole of Sweden, and no transmission restrictions are implemented.

Temporal Scope and Resolution
The model simulates 21 days, with a time granularity of one hour. To run the model, a total net volume of available water for the entire simulation period is given which is based on historical data. As in (Amelin et al. 2009) and (Söder 2013), seasonal storage is thus described by the historical data.

Technology Representation
Hydropower is described in detail, while other production and consumption are described by exogenously provided time series. Moreover, the model focuses on the electricity system only and does not take any storage or DSM technologies into account.

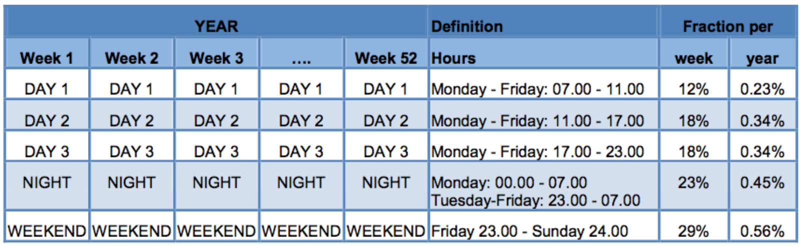
3.3.4 TIMES-Norway - An Energy System Investment Model

In Norway, hydropower constitutes 95-99 % of the yearly power production, and as much as 70 % of the hydropower is controllable (Lind et al. 2013a). It is therefore interesting to study how the hydropower is handled in Norwegian energy system models when trying to find a better way to describe the hydropower in the Swedish counterparts. One such model is TIMES-Norway, which is developed by the Norwegian institute for energy technique (IFE), and uses the modeling tool TIMES just like TIMES-Sweden.

TIMES-Norway is an investment model that minimizes the total discounted cost of energy supply for meeting an exogenously given demand of energy services. The model is similar to TIMES-Sweden, and this overview only discusses some differences between the two models. A complete description of TIMES-Norway can be found in (Lind et al. 2013b).

TIMES-Norway differs from its Swedish counterpart both when it comes to the implementation of hydropower and the choice of time resolution. In the model, each year is divided into 52 weeks, and every week is divided into 5 time slices. This gives a total of 260 time slices per year, which can be compared to 12 time slices per year in TIMES-Sweden. The division in time slices can be seen in figure 5.

Hydropower is divided into hydropower plants with reservoirs and so called run-of-the-river power plants. The inflow is based on historical data for each region and is given by weekly time series. For power plants with reservoirs, water can



YEAR					Definition	Fraction per	
Week 1	**Week 2**	**Week 3**	**....**	**Week 52**	**Hours**	**week**	**year**
DAY 1	DAY 1	DAY 1	DAY 1	DAY 1	Monday - Friday: 07.00 - 11.00	12%	0.23%
DAY 2	DAY 2	DAY 2	DAY 2	DAY 2	Monday - Friday: 11.00 - 17.00	18%	0.34%
DAY 3	DAY 3	DAY 3	DAY 3	DAY 3	Monday - Friday: 17.00 - 23.00	18%	0.34%
NIGHT	NIGHT	NIGHT	NIGHT	NIGHT	Monday: 00.00 - 07.00 Tuesday-Friday: 23.00 - 07.00	23%	0.45%
WEEKEND	WEEKEND	WEEKEND	WEEKEND	WEEKEND	Friday 23.00 - Sunday 24.00	29%	0.56%

Figure 5: Division of time slices in TIMES-Norway. Source: (Lind et al. 2013b)

either be saved to the next week or be utilized to meet the power demand during day time (three time slices) or night. The water can thus be stored both on a day-night level and over longer time periods. At the same time, the description of hydropower is not as detailed as in the previously described models, and hydrological coupling and restrictions for individual plants are not accounted for.

Spatial Scope and Resolution
TIMES-Norway covers the energy system of Norway. Norway is divided into six regions for which energy production, consumption etc. are described by aggregated values. Production and energy conversion are described by availability factors and total installed capacity in each region, and individual plants are thus not distinguishable.

Temporal Scope and Resolution
The time horizon can be set as far ahead as 2050. The time granularity is 260 time steps per year, the division into time steps can be seen in figure 5.

Technology Representation
In contrast to the previously described models, TIMES-Norway includes more sectors than just the power system. Among other things, the model describes endogenously the electricity, heat, hydrogen, biomass and fossil fuel supply systems, and several demand technologies in the industry, transport and residential sectors. The level of detail in the representation of the included technologies is at the same time lower than in the previous models.

3.3.5 Summary

The models' type, time horizon, time granularity and included restrictions can be seen in table 2. The objectives of the different models varies widely, and the description of hydropower varies between aggregated values of installed capacity and seasonal availability for the whole of Sweden to detailed descriptions of single river systems. Even with a rather low temporal and spatial resolution it is possible to describe hydropowers capability of balancing seasonal variations and the physical and legal restrictions related to energy storage in reservoirs. To capture the ability to balance variations at shorter time intervals, however, obviously requires a higher temporal resolution. Furthermore, the restrictions limiting the hydropower's ability to balance variations at shorter time intervals are made up of the available capacity of individual plants and the flexibility of the river systems, which means that a lower spatial resolution is also necessary.

Two of the models include descriptions of prognosis uncertainty of wind power production. In (Amelin et al. 2009), the expected value of hydropower production for all scenarios is optimized, which complicates hydropower scheduling. Lönnberg (2014) uses a static model, where each day is optimized with false information about future wind production, which also complicates scheduling. While both of the models include the difficulties in optimal utilization of water resources, none of the models capture difficulties arising from the extra need of quickly being able to increase and decrease the production in response to unpredicted variations in wind production.

Table 2: A comparative summary over some of the characteristics of the models included in the review.

	Model Type	Time Horizon	Time Granularity	Restrictions				Uncertainty
				Technical	Physical	Legal	Market Related	
Amelin et al. (2009)	Dynamic LP model	One week	One hour	Installed capacities and production factors. In some cases, the model accounts for forbidden production levels and additional costs for start/stop and ramping.	Hydrological coupling, natural inflows, flow time between plants.	Water usage regulations concerning reservoir levels, flow rates, ramping rates and daily differences in reservoir water levels	In some caes, prognosis uncertainty	Partially through stochastic optimization for some weeks
Söder (2013)	Calculations from statistical data	One Year	One hour	Installed capacity (aggregated for entire Sweden) and historical minimal and maximal availability				
Lönnberg (2014)	Static mixed integer optimization model	21 days	One hour	Installed capacities, efficiencies and start-up costs.	Hydrological coupling, natural inflows, flow time between plants.	Water usage regulations concerning reservoir levels and flow rates	Prognosis uncertainty	Yes
TIMES-Norway (Lind et al. 2013)	Dynamic LP model	Up to 50 years	260 time-slices per year	Installed capacity	Natural inflow and total energy storage volume (including legal restrictions)			
TIMES-Sweden	Dynamic LP model	20-50 years	12 time-slices per year	Installed capacity and annual and seasonal availability factors				

4 A TIMES-based Hydropower Model of Lule River

One of the objectives of this thesis is to develop a TIMES-based, long-term energy system model in which the variability of intermittent production and flexibility of hydropower is accounted for. This chapter presents a description of the developed model. Section 4.1 and 4.2 present an overview of the modeled energy system and declare the objective and temporal representation of the model. Thereafter, section 4.3 provides a more detailed description of the implementation of hydropower, and section 4.4 of the implementation of demands and other power generation technologies. Finally, section 4.5 gives an overview of some model-data regarding hydropower and demand and production profiles. Assumptions regarding other technology specific data such as costs, availability factors and efficiencies are presented in the scenario description in chapter 5.

4.1 Overview

A reference energy system (RES) of the simulated energy system can be seen in figure 6. The model includes intermittent production from wind and solar, base load generation from nuclear power plants, biomass power plants and biomass combined heat and power (CHP) and flexible and peak generation from hydropower and gas peak power plants respectively. To adequately describe CHP, which constitutes a significant share of Swedish power generation, a simple description of district heating is included.

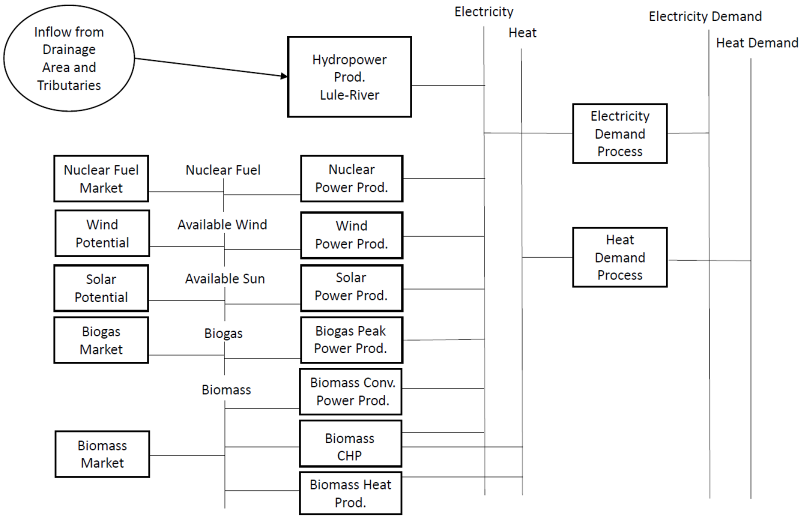


Figure 6: RES of the simulated energy system.

The model is restricted to the hydropower of the Lule-river, focuses solely on the power and district heating sectors and only includes a limited number of generation technologies. Unlike in TIMES-Sweden, no demand sectors or end-use technologies are included and the electricity and heat demand are given by exogenous time series. Furthermore, no costs or restrictions related to the transmission of electricity or heat are included in the model. In addition to the ones included in the RES above, there are also several processes and commodities describing the hydropower of the Lule-river. These are described in section 4.3.

The objective is to minimize the fixed and running costs of all processes, and the objective function can be formulated as:

$$J = \sum_{y \in Y} \sum_{p \in P} \frac{1}{(1+d)^{t-y_0}} \times (N\_CAP[y][p] \times INVCOST[p] + \\ + CAP[y][p] \times FIXCOST[p] + ACT[t][y] \times VARCOST[p]) \tag{8}$$

where Y and P are the sets of all years and processes respectively, y_0 is the first year of the time horizon and d the discount rate. $N\_CAP[y][p]$ is the newly installed capacity of process p at year y, $CAP[y][p]$ is the total installed capacity of process p at year y and $ACT[t][y]$ is the activity of process p at year y. $INVCOST[p]$, $FIXCOST[p]$ and $VARCOST[p]$ are the investment cost, fixed cost and variable cost of process p. During optimization, the production of a commodity must at all points in time be greater than or equal to the consumption. This ensures that the electricity and heat demand is satisfied at all times. For a more detailed description and formulation of all constraints defining the system above, please refer to (Loulou et al. 2016b).

4.2 Temporal Scope and Resolution

Optimization is carried out between 2016 and 2030. The two first periods are one year long, after that the period-length is two years and investment decisions can thus be made every other year. To describe hydropower's ability to balance variations within and between days a high temporal resolution is necessary. Furhermore, a sequential time-slice division is needed if the water content of individual reservoirs (and consequently the production potentials) are to be explicitly described at all times. Therefore, each year is divided into 1460 sequential time-steps of 4 hours. The time-steps are longer than the 1 hour long time-steps of the detailed hydropower models described in chapter 3. Due to the longer time-horizon, this is viewed as necessary to facilitate data-handling and shorten computational times.

The division in time slices can be seen in table 3. TIMES is constructed so that one year represents all years within a period. Therefore, hydro storage between years is not included and reservoir water levels are set for the beginning and end of each year. The hydrological preconditions in terms of water resources are therefore the same for each year.

Table 3: Time-slice division of the developed model.

Time-slices				Fraction Per Year
Day 1	Day 2	...	Day 365	
00:00 - 04:00	00:00 - 04:00	00:00 - 04:00	00:00 - 04:00	0.0045 %
04:00 - 08:00	04:00 - 08:00	04:00 - 08:00	04:00 - 08:00	0.0045 %
08:00 - 12:00	08:00 - 12:00	08:00 - 12:00	08:00 - 12:00	0.0045 %
12:00 - 16:00	12:00 - 16:00	12:00 - 16:00	12:00 - 16:00	0.0045 %
16:00 - 20:00	16:00 - 20:00	16:00 - 20:00	16:00 - 20:00	0.0045 %
20:00 - 24:00	20:00 - 24:00	20:00 - 24:00	20:00 - 24:00	0.0045 %

4.3 Hydropower

The hydropower system of the Lule River and some reservoir and plant specific data can be seen in figure 8. All interconnections between power plants and reservoirs are defined according to the figure.

An overview of the implementation of two sequential hydropower plants is shown in figure 7. Each plant and accompanying reservoir are described by one process describing the power plant, one process describing water spill over the plant, one storage process describing the water content in the reservoir and one commodity representing the water. At all points in time the production of the water commodity has to equal the consumption. Natural inflows and inflows from precedent hydropower plant and spill processes are thus either utilized by, or spilled past, the subsequent plant, or stored in the reservoir.

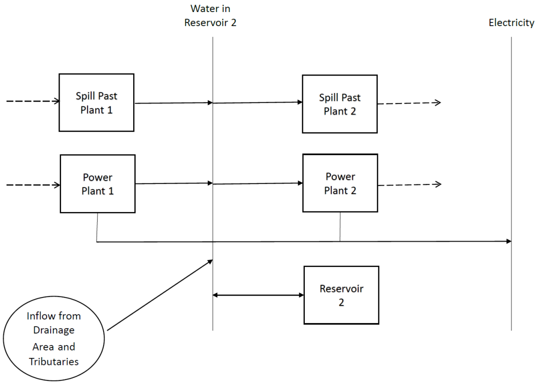


Figure 7: The implementation of two sequential hydropower plants.

Each spill and power plant process is defined by the incoming and outgoing commodities and the relationships between them. The activity of a process is restricted by its capacity and restrictions concerning commodity flows. The water contents in reservoirs are described by water volumes, and physical and legal restrictions concerning minimal and maximal water levels are therefore transformed to restrictions in water volumes. Furthermore, the volumes are

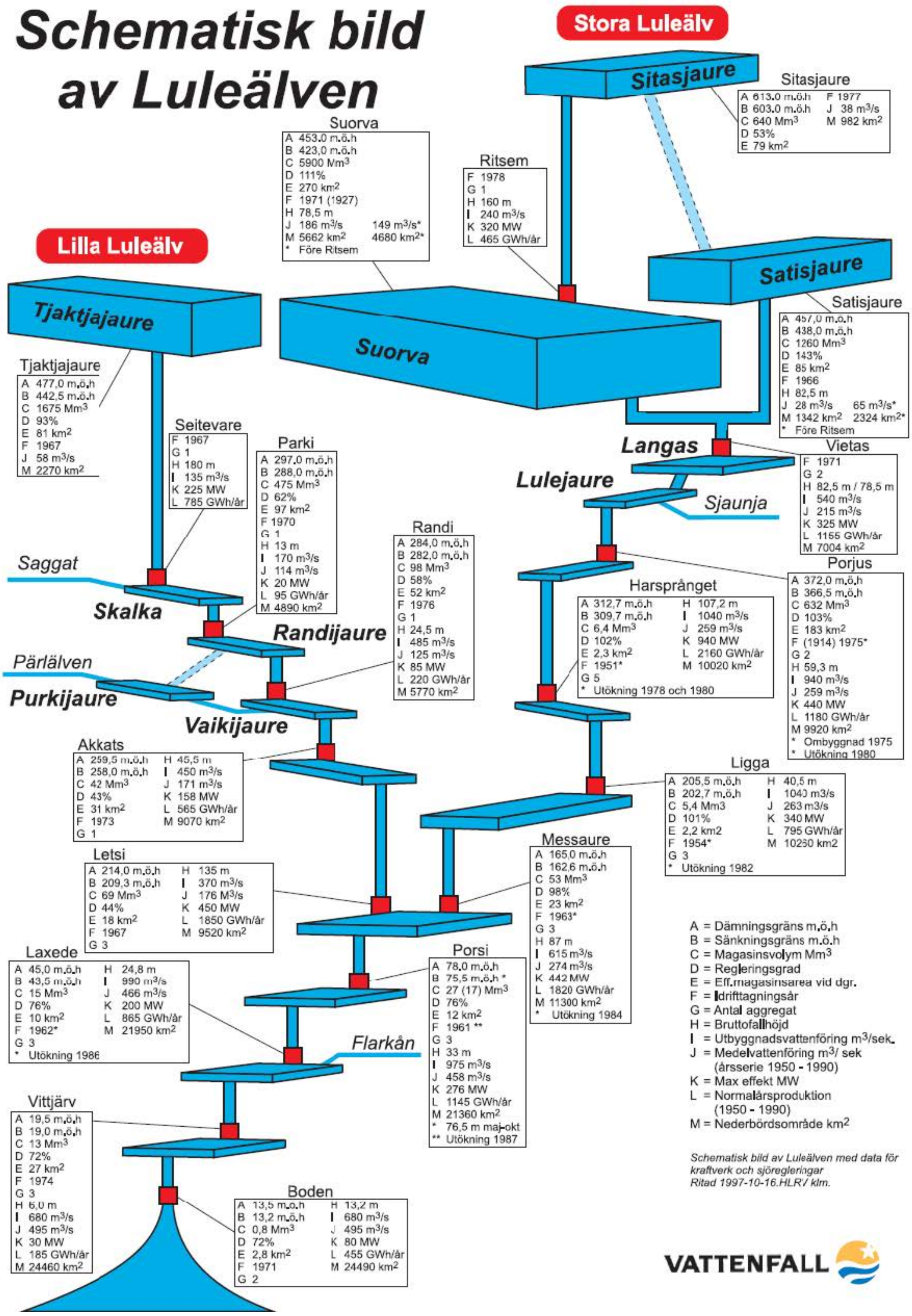


Figure 8: The hydropower system of the Lule river. Source: (Bruce et al. 2016)

rescaled to describe the active volume, which is defined as the real volume subtracted by the minimal allowed. This makes it possible to describe minimal and maximal water volumes by:

$$0 \leq V[r] \leq \bar{V}[r] \tag{9}$$

where $V[r]$ is the volume of water in reservoir process r and $\bar{V}[r]$ is the storage capacity of r. Physically, $\bar{V}[r]$ represents the volume that can be stored in reservoir r while also taking legal restrictions into account. Consequently, empty and full reservoir processes do not represent empty and full reservoirs, but rather reservoirs where the water level is at the minimal and maximal allowed level respectively.

4.3.1 Technical Restrictions

Installed capacities and production factors are defined for each power plant process. As in (Amelin et al. 2009), the dependency of head is neglected and the power production is approximated as a function of water flow. According to (Amelin et al. 2009), this is not a gross simplification since the dependency of head is small compared to the dependency of water flow. Furthermore, this function is approximated as linear, i.e. one production factor is used at all production levels. The model thus does not account for efficiency losses due to power production at disadvantageous production levels. Neither does it include any prohibitions of certain production levels due to increased wear and tear. A model that included these would describe the system more accurately. However, according to (Amelin et al. 2009), the efficiency probably only has a marginal impact on hydropower's regulating capability.

4.3.2 Physical Restrictions

The model includes physical restrictions in terms of hydrological coupling, natural inflow and flow times between power stations. Physical restrictions concerning reservoir water levels are also accounted for in the definitions of reservoir storage capacities. Hydrological coupling is described by connecting all reservoir, power plant and spill processes according to figure 7 and 8. Mathematically, the water system is described by:

$$\begin{aligned} \forall c, t : N[c][t] + \sum_{p \in S_{o,c}} F[p][t] + \sum_{p \in Q_{o,c}} F[p][t] + \sum_{r \in R_c} F_{out}[r][t] - \\ -\Big(\sum_{p \in S_{i,c}} F[p][t] + \sum_{p \in Q_{i,c}} F[p][t] + \sum_{r \in R_c} F_{in}[r][t] \Big) = 0 \end{aligned} \tag{10}$$

where c denotes water commodity and t time-slice. $S_{o,c}$ and $Q_{o,c}$ are the sets of all spill and plant processes having c as one of its outputs, and $S_{i,c}$ and $Q_{i,c}$ are the sets of all spill and plant processes having c as one of its inputs. R_c is the set of all reservoir processes storing water commodity c, $F[p][t]$ is the amount of water flowing through process p at time-slice t and $F_{in}[r][t]$ and $F_{out}[r][t]$ are the amounts of water flowing in and out of r at t respectively. Finally, $N[c][t]$ is the amount of natural inflow from drainage areas and tributaries, which is given by exogenous time-series.

With the exception of the flow time between Porsi and Laxede, all flow times between power stations are significantly shorter than the model's time granularity of four hours and are therefore overlooked by the model. The flow time between Porsi and Laxede is approximately five hours. To represent this delay, the flow time is rounded to four hours and the following constraints are included:

$$F[Pors][t-1] \leq V[Lax][t] \leq \bar{V}[Lax] + F[Pors][t-1] \tag{11}$$

where $V[Lax][t]$ is the water volume stored in the reservoir process Laxede at the beginning of time-slice t, $\bar{V}[Lax]$ is the storage capacity and $F[Pors][t-1]$ is the the amount of water flowing through the Porsi plant and spill processes during the time-slice prior to t. The left inequality ensures that the minimal amount of water stored in the reservoir at the beginning of time-slice t is greater than the amount flowing through Porsi at time-slice $t-1$, i.e. that none of the water flowing through Porsi will also flow through Laxede during the same time-slice. The right inequality makes it possible for the Laxede reservoir process to contain a greater amount of water than defined by physical and legal restrictions, since water from Porsi during one time-slice (four hours) will be in the river systems between the Porsi power station and the Laxede reservoir. The Laxede reservoir process can thus be interpreted to represent both the Laxede reservoir and the river system from Porsi.

4.3.3 Legal Restrictions

Legal restrictions concerning reservoir water levels are accounted for in defining the storage capacity of each reservoir process (see section 4.3.1). The model also includes legal restrictions concerning minimum water discharge by introducing lower limits for the combined water discharge from spill and plant processes.

The model does not include any physical or legal boundaries on maximum water discharges. According to (Nyström 2017), the maximum discharge is restricted by physical (i.e. the capacity of spillways) rather than legal restrictions. Moreover, the capacity of spillways is considerably larger than the maximal discharge from the power plants (restricted by the power generation capacity) in order for the system to be able to deal with high inflows during the spring season (Nyström 2017). Since water spill should be kept at low levels during simulation in order to reduce energy production costs it is assumed that these upper boundaries are not exceeded.

4.3.4 Market Related Restrictions

The electricity market is made up of the demand and power production technologies shown in figure 6. The model minimizes the total system cost or, put another way, maximizes the producers and consumers surplus. The model thus simulates a perfect market where energy is consumed at the lowest cost. The model assumes perfect foresight, and therefore the operation of hydropower is carried out with full knowledge of future energy prices and natural inflows. It thus does not account for energy losses due to non-optimal utilization of water resources.

In Sweden, the automatic reserves[4] are made up almost entirely of hydropower. The reserve places upper and lower boundaries of the total momentary production of hydropower. These upper and lower boundaries are implemented as:

$$\forall t : RES_{down} \leq \sum_{p \in Q} \frac{H[p][t]}{4} \leq \sum_{p \in Q} Cap[p] - RES_{up} \tag{12}$$

where $H[p][t]$ is the hydropower production of process p during time-slice t and RES_{down} and RES_{up} are the reserve requirements for a production decrease and increase respectively.

As mentioned in section 3.1.4, an increased share of intermittent production places additional margin requirements on hydropower due to the difficulty of correctly predicting the production levels in advance. The sizes of these margins depend on the magnitude of the forecast errors as well as the flexibility of other production and consumption technologies. In the standard case, the model does not account for these additional margins and the hydropower production is determined under the assumption of perfect forecasts. To get an idea of how larger production margins impact the balancing capability the system is also optimized in a case where production restrictions are included which ensure that there is sufficient available capacity to increase the hydropower production in response to production losses from intermittent sources. Since the model predicts intermittent production from mainly wind power (see chapter 6), the implementation is limited to forecast errors concerning wind power.

An increased share of wind power is expected to only have a marginal impact on the size of the automatic reserves (Svenska Kraftnät 2013). An increase impacts rather the sizes and frequency of which energy is traded in the regulation market as well as the size and activation frequency of the manual reserves[5]. In contrast to the automatic reserves, the production facilities (or consumers) acting on these markets are not exclusively made up of hydropower. The manual reserves mainly consist of peak gas turbines and participation on the regulation market is voluntary and the distribution between producing and consuming participants is decided continuously throughout the year (Svenska Kraftnät 2013). In reality, the hydropower production margins will therefore depend on the potential and costs of the other actors. However, in this case it is assumed that hydropower is able to balance all production reductions caused by errors in wind forecasts made 3 hours in advance in 95% of the cases. This can be interpreted as making the following assumptions regarding the behaviour of the actors in the electricity market:

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[4] Sv: Reserver för sekundärreglering

[5] Sv: Reserver för tertiärreglering

1. All actors on the electricity market are assumed to have access to continously updated forecasts and adjust their bids on the intra-day and regulation markets down to 3 hours in advance. According to (Svenska Kraftnät 2013), this corresponds well with how the actors currently behave.
2. Margins on hydropower are enforced to ensure that hydropower alone is able to balance any differences between the wind production schemes (based on the 3 hours in advance forecasts) and the actual production in 95% of the cases. The margins only concern upregulation.
3. In the remaining 5% of the cases, other existing power production capacity is assumed to be able to be activated and aid hydropower in responding to the balancing demand.

The production constraints are implented as:

$$\forall t, y : \sum_{p \in Q} \frac{H[p][t][y]}{4} \leq \sum_{p \in Q} Cap[p] - RES_{up} - \frac{FE_{P95}[2013-2015]}{CAP[Wind][2013-2015]} \times CAP[Wind][y]. \tag{13}$$

where $CAP[Wind][2013-2015]$ is the average installed capacity during the period 2013-2015 and $FE_{P95}[2013-2015]$ depicts the 95th percentile of upregulation caused by wind forecast errors during the same period, which is obtained from (Bruce et al. 2016). The 95th percentile of the forecast error is assumed to grow linearly with installed wind capacity. During time-slices where wind power production is lower than the margin (13) is replaced by:

$$\sum_{p \in Q} \frac{H[p][t][y]}{4} \leq \sum_{p \in Q} Cap[p] - RES_{up} - \frac{W[t]}{4}. \tag{14}$$

where $W[t]$ is the wind power production during time-slice t.

Equations (12-14) only ensure that there is sufficient available capacity to increase or decrease hydropower production and do not account for the availability of energy resources in reservoirs. Neither are the forecasts errors explicitly simulated. According to (Bruce et al. 2016) the availability of capacity will probably place stricter restrictions on the flexibility of hydropower than the availability of energy resources, since the errors in predicted energy amounts are estimated to be small compared to the energy stored in reservoirs and water in the worst case can be spilled upstream to provide water resources for plants downstream. It should be noted, however, that the additional amounts of spill which this could imply is not captured by the model.

4.4 Demands and Other Power Generation Technologies

The included demands and power generation technologies can be seen in figure 6. The model focuses on hydropower, and other power generation technologies are implemented in a simpler manner.

Wind, solar and nuclear power production and electricity and heat demands are defined by exogenous load curves based on the operation and demands of a previous year. The daily, weekly and seasonal variations in production and demand within the year thus remain fixed. For nuclear power and electricity and heat demands the yearly, total load is also specified exogenously. As for wind and solar power merely the operational patterns are fixed, and investments in new capacity can be made throughout the entire time horizon. The yearly production can therefore grow unlimitedly, while the relation between installed capacity and production at a specific time-slice remains fixed. Hence the smoothing effect, i.e. the decrease in variations in intermittent production due to an increased installed capacity, is not accounted for by the model.

The production from all other power generation technologies is determined endogenously at each time-slice. The production levels are determined from installed capacities, availability factors, production costs, demands and the competitiveness of other power generation. To ensure that the flexibility of biomass and CHP power and heat generation is not overestimated, the activities of these plants are restricted to remain constant during each night (time-slices -H6, -H1, and -H2) and day (time-slices -H3, -H4 and -H5).

4.4.1 Combined Heat and Power

To adequately describe CHP a simple description of the district heating market is included. The market contains heat production from biomass CHP and biomass direct combustion only. The CHP plant process is modeled as an extraction turbine CHP plant, which means that the electricity to heat ratio is flexible. Figure 9 shows an illustration of the area of operation. The operation can alter between condensing mode, where only electricity is produced, and back pressure mode where maximum heat is obtained and the overall efficiency is at its peak. The process is defined by specifying the electrical efficiency at condensing mode, the heat to power coefficient at back pressure mode and the electricity loss per unit of heat gained. From these factors, electricity and heat output can be determined at all operation modes.

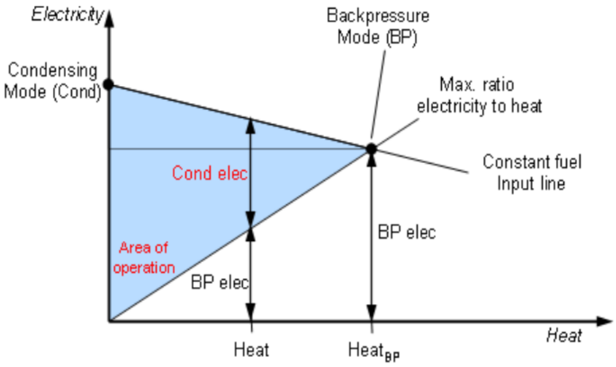

Figure 9: Illustration of the area of operation of the CHP process. Source: (Gargiulo 2009)

4.5 Data

Information regarding reservoir volumes (including legal restrictions) and installed capacities of each hydropower plant is taken from figure 8. The information is rather old (from 1997), however, according to (Engström 2017) there have not been any major changes since then and the information is therefore deemed applicable. Legal restrictions concerning minimum water discharge is provided by (Engström 2017), and natural inflows and reservoir water levels (at the beginning and end of the year) are provided by (Nyström 2017). The automatic reserve requirements for the whole of Sweden are taken from (Svenska Kraftnät 2015) and distributed to the hydropower system of the Lule River according to its share of installed hydropower capacity.

The natural inflows and reservoir water levels are given for 2012. 2012 is characterized as a so called water year, i.e. a year with high hydropower production levels. During 2012 Swedish hydropower produced 79 TWh, which can be compared with the average between 2005 and 2015: 68 TWh. Because of the method by which the simulated system is defined (see section 5.2.1), the choice of data year does not cause an overestimation of the hydropower's share of power generation. It might, however, lead to an underevaluation of the regulating capability, since the amount of undeployed capacity is lower at high production levels and the room for adaptation thus smaller (Bruce et al. 2016).

Load curves of wind, solar and nuclear production and electricity demands consist of data for the whole of Sweden during 2016, and are taken from (Svenska Kraftnät 2017). For the production technologies, the load curves are implemented by defining the fixed ratios between electricity output and installed power production capacity. These ratios are determined from the hourly production levels of (Svenska Kraftnät 2017) and information of installed capacities taken from (Energimyndigheten 2017). The heat demand profile is taken from TIMES-Sweden. This means that the data is distributed across the finer time-slice division of the model and the heat demand profile is consequently the same for all time-slices within the same season and time of day. Assumptions regarding other process and commodity specific data, such as costs, availability factors and efficiencies are presented in chapter 5.

5 Simulations

In order to compare the results of the developed model with the ones of TIMES-Sweden, a new model is created whose temporal representation and hydropower implementation is defined as in TIMES-Sweden but whose scope and technology representation are limited to the ones of the developed model. The models are thereafter applied to study the development of the Swedish power system in a scenario where nuclear is gradually phased out and an increase in intermittent production can be expected. This chapter contains a short description of the comparative model and a description of the studied case.

5.1 Simple Model

The comparative model, henceforth called the simple model, covers the same sectors and technologies as the detailed model described in section 4, and all included commodities and processes can be seen in figure 6. It differs from the detailed model in temporal resolution and the representation of hydropower, which are implemented as in TIMES-Sweden. The time-slice division can be seen in table 4. In the model, the peak hour time-slice corresponds to the hour of the day in which the electricity demand is at its peak. This hour is not added to the calculations of activity during the day time-slice, and the day time-slice therefore represents 11 hours only.

Table 4: Time-slice division of the comparative model.

Time-slices		**Fraction Per Year**
R 16/3 - 31/5	**D**: 08:00 - 20:00	0.097 %
	N: 20:00 - 08:00	0.105 %
	P: Daily Peak Hour	0.009 %
S 1/6 - 30/8	**D**: 08:00 - 20:00	0.114 %
	N: 20:00 - 08:00	0.125 %
	P: Daily Peak Hour	0.010 %
F 31/8 - 15/11	**D**: 08:00 - 20:00	0.097 %
	N: 20:00 - 08:00	0.105 %
	P: Daily Peak Hour	0.009 %
W 16/11 - 15/3	**D**: 08:00 - 20:00	0.151 %
	N: 20:00 - 08:00	0.164 %
	P: Daily Peak Hour	0.014 %

Hydropower is represented by two processes corresponding to hydropower plants that are easily regulated and plants that have limited reservoirs. As in TIMES-Sweden, the installed capacity is divided equally over the two processes. The annual availability factors are adjusted so that the annual hydropower production is the same in the two models. The time-slice specific availability factors are defined according to TIMES-Sweden, and can be seen in table 1 in section 2.3.1.

As in the detailed model, wind solar and nuclear power production and electricity and heat demands are defined by exogenous load curves. The load curves are taken for the same year as for the detailed model and sorted according to the the time-slice definitions shown in table 4. The production from all other power generation technologies is determined endogenously at each time-slice. Efficiencies, availability factors, costs and other technology specific data are the same in both models.

5.2 Case Study

The case study is carried out in order to compare the models' calculations of the future power system's optimal composition and to investigate the extent to which the flexibility of hydropower can enable an increased integration of production from intermittent sources. Optimizations are performed for the period 2016-2030. To represent a scenario where intermittent production capacity is integrated to the power system, nuclear power is assumed to decrease linearly from full capacity 2020 to zero capacity 2030. The production therefore has to be replaced by new production from any combination of the technologies shown in figure 6. The models only include production from renewable resources. This is in line with Swedish long term goals concerning power and heat production.

5.2.1 Simulated System

The simulated energy system represents a simplified mini-version of the Swedish power and district heating sectors, where installed capacities and demands are scaled so that the annual share of hydropower production from the Lule River in the modeled system equals the total annual share of hydropower production in the real system. This means that annual production and consumption volumes are provided for the whole of Sweden. The annual electricity and district heating demands are therafter calculated by:

$$\forall c : D_{model}[c] = D_{Sweden}[c] \times \frac{Hyd_{Lule}}{Hyd_{Sweden}} \tag{15}$$

where D_{Sweden} is the annual demand of commodity c for the whole of Sweden and Hyd_{Sweden} and Hyd_{Lule} the hydropower production of the whole of Sweden and the Lule River respectively. Installed capacities at the start year are calculated by:

$$\forall p : Cap_{model}[p] = \frac{Prod_{model}[p]}{8760 \times AF_{annual}[p]} \tag{16}$$

where $Cap_{model}[p]$ is the installed capacity of process p at the start year and $AF_{annual}[p]$ the maximum annual availability of process p (including cases where time-slice specific AFs impose stricter restrictions than the annual AF). $Prod_{model}[p]$ is the annual power production of process p at the start year in the modeled system, and is calculated by:

$$\forall p : Prod_{model}[p] = Prod_{Sweden}[p] \times \frac{Hyd_{Lule}}{Hyd_{Sweden}} \tag{17}$$

where $Prod_{Sweden}[p]$ is the annual production of process p for the whole of Sweden. All data concerning the annual production for the whole of Sweden are adjusted to exclude import and export, since these are not accounted for by the models. It is assumed that the annual amounts of export and import are evenly distributed over the power production technologies according to installed capacity.

5.2.2 Main Assumptions

The annual electricity and district heating demands and installed power generation capacities of each period are shown in table 5. The installed capacity of hydropower and nuclear are exogenously defined for each time-period. All other power generation capacities are determined endogenously after 2016. Electricity and heat demands are assumed to remain at initial levels throughout the time horizon.

Installed capacities and demands are determined by equations (15-17). The annual electricity demand and production per generation technology are provided by (Svenska kraftnät 2017) and taken for 2016. The heat demand is provided by (Energimyndigheten 2017) for 2015 and excludes district heating from waste heat and heat pumps. At the start year, district heating production from CHP is assumed to provide 40 % of the total demand (including heat from waste heat and heat pumps), based on (Energimyndigheten 2015). The remaining district heating is assumed to be provided by conventional heat production. Both CHP and conventional heat production are assumed to consist of biomass fired plants only.

Table 5: Assumptions regarding electricity and district heating demands and installed production capacities.

	Demand [PJ/year]								
	2016	**2017**	**2018**	**2020**	**2022**	**2024**	**2026**	**2028**	**2030**
Electicity	144	144	144	144	144	144	144	144	144
Heat	37	37	37	37	37	37	37	37	37
	Installed Capacity [MW]								
	2016	**2017**	**2018**	**2020**	**2022**	**2024**	**2026**	**2028**	**2030**
Hydropower	4 313	4 313	4 313	4 313	4 313	4 313	4 313	4 313	4 313
Nuclear	2 661	2 661	2 661	2 661	2 129	1 597	1 065	532	0
Wind	≥1 649	≥1 649	≥1 649	≥1 649	≥1 649	≥1 649	≥1 649	≥1 649	≥1 649
Solar	≥14	≥14	≥14	≥14	≥14	≥14	≥14	≥14	≥14
Biogas-Peak	≥ 0	≥ 0	≥ 0	≥ 0	≥ 0	≥ 0	≥ 0	≥ 0	≥ 0
Biomass El.	≥ 0	≥ 0	≥ 0	≥ 0	≥ 0	≥ 0	≥ 0	≥ 0	≥ 0
Biomass CHP[*]	≥ 486	≥ 486	≥ 486	≥ 486	≥ 486	≥ 486	≥ 486	≥ 486	≥ 486
Biomass Heat[**]	≥1 252	≥1 252	≥1 252	≥1 252	≥1 252	≥1 252	≥1 252	≥1 252	≥1 252

[*] Electricity production capacity at condensing mode.

[**] District heating production capacity.

Table 6 shows assumptions regarding the efficiencies, life times, investment costs, fixed operation and management costs and availability factors (AF) of the included power and district heating production technologies. The assumptions are based on the ones of the EU TIMES-model developed by Simoes et al. (2013) regarding technology characteristics in 2020. In (Simoes et al. 2013), each power generation technology is described by several processes to characterize different types of plants. For example, wind power is described by 9 processes corresponding to plants of different size, generation and onshore/offshore location. In this case study each technology is represented by one process only. Table 6 contains the specification in (Simoes et al. 2013) of the specific technologies for which the assumptions are extracted.

The AFs are shown for the biogas and biomass fueled power generation technologies only. As mentioned, power generation from nuclear, wind and solar in each time-slice is defined by exogenous load curves based on the ratios between the production and installed capacities of 2016. As for hydropower, full availability is assumed in the case of the detailed hydropower model and the time-slice specific AFs of the simple model can be seen in table 1.

The total efficiency at back-pressure mode and the electricity efficiency at condensing mode of CHP are based on (Simoes et al. 2013). The electricity efficiency at back-pressure mode is calculated from the two other efficiencies and the assumptions of CHP electricity and heat production at the start year.

Table 6: Assumptions of the characteristics of power and district heating production technologies.

	Specification in (Simoes et al. 2013)	**Efficiency** [%]	**Life Time** [Years]	**Inv.Cost** [€/kW]	**Fixed O&M** [€/kW]	**AF** [%]
Hydropower	Lake large scale cheap hydroelectricity > 10 MW	-	-	-	12	-
Nuclear	3rd generation LWR planned	43	-	-	-	-
Wind	Wind onshore 3 high (IES class I)	100	25	1380	29	-
Solar	Solar PV roof 0.1-10 MWp	100	30	1065	16	-
Biogas-Peak	OCGT Peak device conventional	39	15	486	12	90
Biomass El.	Steam turbine biomass solid conventional	35	30	2595	91	90
Biomass CHP	Steam turbine 2	100* 24** 35***	30	2271	45	90
Biomass Heat	Wood chips boiler	88	25	474	20	90

*Total efficiceny at back-pressure mode.
**Electricity efficiceny at back-pressure mode.
***Electricity efficiceny at condensing mode.

Assumptions concerning the production costs of biogas, biomass and nuclear power are shown in table 7. The cost of biogas production is based on the average costs of raw gas production and distribution as calculated by (Vestman et al. 2014). The cost of biomass production is based on the price of wood chips[6] and is provided by (Energimyndigheten 2017). As for nuclear power, the cost

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[6] Sv: Skogsflis.

depicts the total cost of power production (excluding taxes) and is based on the costs of the Forsmark and Ringhals power plants (Vattenfall 2017a)(Vattenfall 2017b).

Table 7: Production costs of biogas, biomass and nuclear power.

	Production Cost [€/MWh]
Biogas	106
Biomass (Wood Chips)	20
Nuclear Power	24

5.2.3 Peaking Constraint

Both models include a peaking constraint to ensure that there is sufficient capacity to handle production shortfall due to uncertainties, unplanned equipment downtime and random peak demand that exceeds the average. The constraint is formulated according to equation (1) and the fractions, PF, of the technologies' capacity that is allowed to contribute to meet the peak load are specified as in TIMES-Sweden. The two models are enforced to be able to meet the same peak load which is determined by the reserve coefficient of TIMES-Sweden multiplied with the power demand at the winter peak time-slice of the comparative model (where demand is at its peak). The peak load and the fraction PF for each technology are shown in table 8.

Table 8: The peak load and fractions PF of each power production technology.

	Peak Load [MW]
Electricity demand	106
	Peak Fraction (PF) [%]
Hydropower	90
Nuclear	90
Wind	30
Solar	0
Biogas-Peak	90
Biomass-El	90
Biomass-CHP	90

6 Results

This chapter presents the results of the case study. The purpose of the study is to investigate how the model results of the future power system's optimal composition are impacted when the technical, physical, legal and market related restrictions of hydropower are represented in greater detail and a higher temporal resolution is enforced. Furthermore, it aims to explore the extent to which an incorporation of intermittent production is limited by the restrictions.

First, the effects of including more detailed descriptions of hydropower characteristics and enforcing higher temporal resolutions in long-term energy system models are investigated by comparing the developed (”detailed”) and simple models' calculations of optimal capacity installments and allocation of power generation. The detailed model's results of installed capacity and allocation of power generation at the end of the time horizon also provide insights to the extent to which Swedish hydropower is able to balance variations from increasingly high shares of intermittent production, and the extent to which additional power production from other peak and base load generation technologies is necessary to keep the system in balance.

To explore how the representation affects how hydropower is optimally utilized in the models and how the utilization changes when more intermittent production is integrated to the power system, the load factors of hydropower are therafter compared for the starting and final years. For the detailed model, it is also investigated how higher shares of power from intermittent sources affect the amount of water spill.

Finally, the installed capacity and allocation of power generation of the detailed model are also computed in a case where additional margin requirements on hydropower for unexpected decreases in wind power production are enforced. This is done in order to get an idea of how larger production margins impact the balancing capability of the system.

6.1 Installed Capacity

Figure 10 shows the installed power generation capacity in 2020 and 2030 for the detailed and simple models described in chapters 4 and 5 respectively. In both cases, the phased out nuclear power capacity is replaced by a large expansion of wind power accompanied by increases in peak and CHP capacity. The main difference between the results concerns installed peak and CHP capacity. In 2030, installed peak and CHP capacity for the detailed model amounts to 2241 MW and 774 MW respectively, which can be compared to 1691 MW and 485 MW for the simple model. With the simple model, the flexibility of the power system is overestimated and this results in a lower investment in base load capacity (by 287 MW) and peaking capacity (by 550 MW).

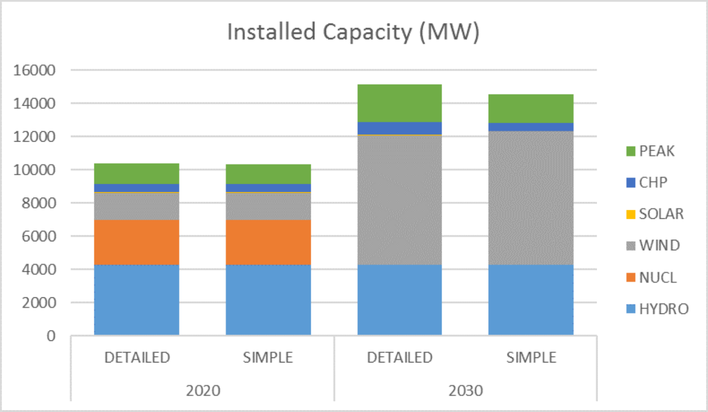

Figure 10: Installed power generation capacity in 2020 and 2030 for the detailed and simple models.

6.2 Power Generation

Figure 11 displays the generated power per production technology, comparing the results of the detailed model with the ones of the simple model. It can be seen that the annual power generation from CHP in 2030 is larger for the detailed model (3.58 TWh compared to 2.23 TWh) and generation from wind is lower for the detailed model (20.09 TWh compared to 20.64 TWh). For the detailed model, the total annual power production in 2030 exceeds the annual demand by 0.93 TWh, indicating that there are occasions where excess production is unavoidable.

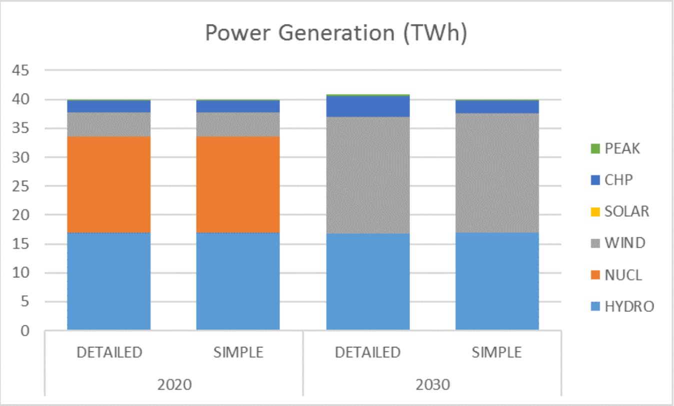

Figure 11: Annual power generation per production technology in 2020 and 2030 for the detailed and simple models.

Looking at the change over time the peak generation increases from 0.03 TWh in 2020 to 0.27 TWh in 2030 for the detailed model, which can be compared to a slight decrease from 0.05 TWh to 0.04 TWh for the simple model. Although quantitatively a small change this means that peak generation in the case of the detailed model increases almost tenfold from 2020 to 2030, which indicates an increase in the number of occasions where less expensive production capacity is not sufficient. Figure 12 shows the daily power generation per production technology during 2030 for the detailed model. As can be seen in the figure, peak generation is activated during days with high electricity demands combined with low wind power production levels. These occasions are not accounted for by the simple model since the production and demand are given as averages over several days. The inability to capture these occasions explains the simple model's underestimation of investments in peak generation. It also explains the underestimation of production from base load generation, since the cost-effectivness of CHP increases compared to the combined system cost of wind and balancing power as the need for expensive peak generation increases.

For the detailed model, the expansion of CHP implies that the combined system cost of additional intermittent and balancing power exceeds the cost of a CHP expansion. This indicates that for the studied system, the extent to which the integration of intermittent production can be balanced by a more flexible utilization of hydropower has reached its upper limit. The potential and socio-economical suitability of wind power beyond the amount which can be balanced by hydropower will depend on the costs and potentials of other existing base load, peak and flexible power generation (and consumption) technologies, which are only very simplistically represented in this case study.

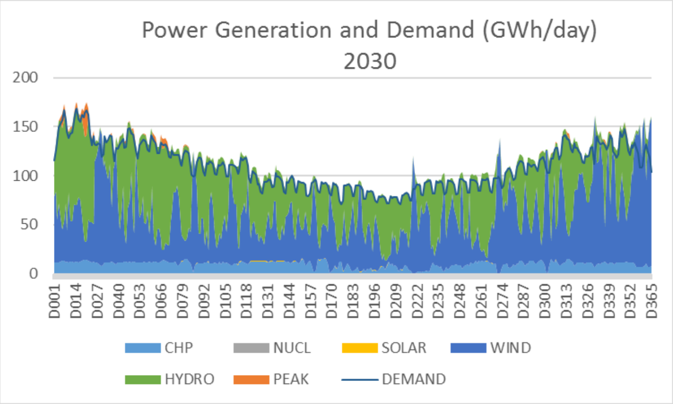

Figure 12: Daily power generation per production technology in 2030 for the detailed model.

Although the integration of intermittent production reaches its economic potential, the detailed model results of installed capacity and power generatation in 2030 indicate that Swedish hydropower is capable of balancing production variations from high shares of intermittent production. For the case study, installed intermittent production capacity increases by over 370%, and in 2030 the production makes up ca. 50% of the annual power production. The flexibility of the studied hydropower system is also illustrated by figure 12. For most of the year the system is able to balance all production variations from wind power generation. The momentary hydropower production ranges from 31 MW to 4165 MW, which are the lower and upper limits as defined by installed capacities and the capacity constraints of equation (12). Furthermore, the hydropower production level is at its upper limit during 100 % of the time-slices in which peak generation is activated. This indicates that for the simulated system, the hydropower's capability of balancing intermittent production is primarily restricted by the available capacity rather than the hydrological coupling or water usage regulations of the river. It also suggests that it would be of interest to include a more detailed representation of electricity transmission, since the transmission capacity may place even stricter restricions during occasions with high hydropower production demands.

For the detailed model, the annual hydropower production in 2016 amounts to 16.88 TWh. This can be compared to the production of the Lule River during 2012, the year from which the hydrological conditions are taken, which amounted to 16.52 TWh. The model thus overestimates the annual production by ca. 2 %, which is probably due to the assumptions of perfect forecasts and full availability of the power plants.

6.3 Hydropower Utilization

Figures 13 and 14 show the seasonal load factors of hydropower in 2016 and 2030 respectively. The load factors depict the percentage of the installed capacity being utilized within a specific period of time[7], and are shown according to the time-slice division of the simple model (and TIMES-Sweden). Comparing the load factors in 2016 and 2030, the major difference is a movement of hydropower utilization from winter to spring. This can be easily understood by looking at the daily demand and wind power production in figure 12. As the wind production increases the residual load is increasingly shifted from time-periods with high demand towards time-periods with low wind availability. This means that the seasonal utilization of hydropower in a future energy system with high shares of wind power generation to a large extent will depend on the seasonal variability of wind power production.

Comparing the results of the two models, it can be noticed that the load factors of the day time-slices are larger for the detailed model while the load factors of the night time-slices are smaller. This is probably an effect of the simple model not capturing the wind and demand variability during and between days. In the detailed model, hydropower is the only flexible technology used to balance variations at shorter time-frames (expensive peak generation is avoided when possible), while in the simple model balancing is divided equally between the activated technologies (since the production and demand are given as averages). Hydropower production in the case of the detailed model therefore will be shifted towards day-time, where the variations in residual load are larger, and away from night-time. For the studied system, the simple model's inability to capture this effect probably only has a small effect on investment decisions, since the production of other power generation technologies probably could be shifted in the opposite direction if necessary. However, it does show that the simple model partially neglects the need for flexible power generation, which means that the value of flexible production and consumption technologies is being

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[7] I.e: Load Factor = $\frac{\text{Production}}{\text{Installed Capacity} \times \text{Hours}}$

underestimated by the model. Comparing the load factors of entire seasons the differences between the two models are small. This indicates that the seasonal flexibility can be described fairly well by the more limited representation of the simple model, which also points out the simulated hydropower system's good ability to store energy between longer periods.

The figures also depict the maximal load factors of hydropower in the simple model, as defined by the availability factors. For the simple model, the load factor reaches its maximum during the RP, FP and WP time-slices. As previously shown, the simulated hydropower system is very flexible and is operated at the upper production limit during several occasions, which suggests that the load factors during peak hours could probably be higher. This means that the simple model partially underestimates the flexibility of the hydropower system. However, the results of installed capacity and allocation of power production suggest that the effects on the power system's composition are relatively small compared to the overall overestimation of the power system's flexibility.

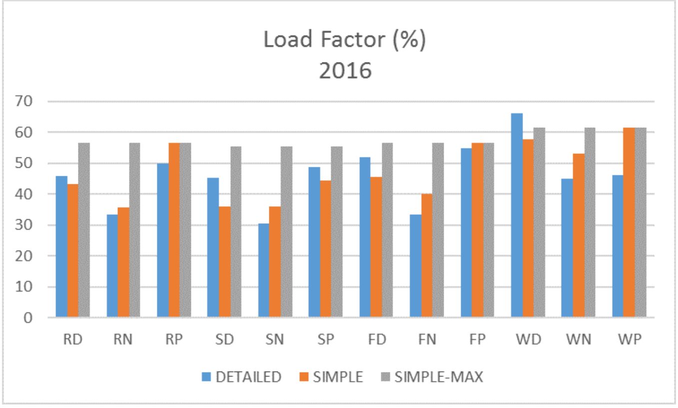

Figure 13: Load factors of hydropower in 2016 for the detailed and simple models.

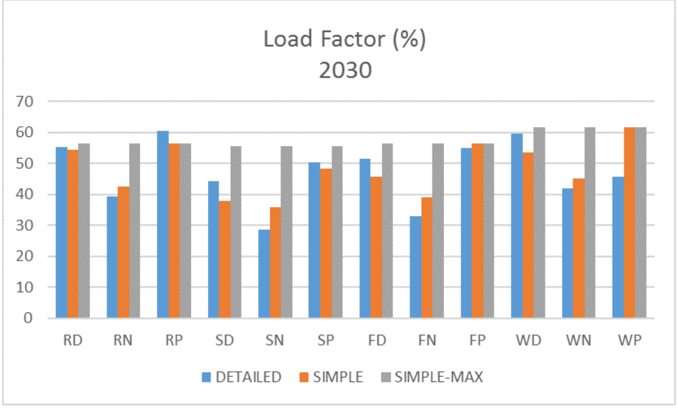

Figure 14: Load factors of hydropower in 2030 for the detailed and simple models.

Changed operational patterns of hydropower due to increased balancing requirements might lead to an increased amount of water spill. Increased spilling has additional effects on the power system since the resulting loss in annual hydropower production has to be replaced. Figure 15 shows the total amount of water spilled past the hydropower facilities in the detailed model. The spill increases from almost 2000 Mm^3 in 2016 to around 5000 Mm^3 in 2030. Figure 16 shows the daily water spillage during 2030, along with the daily hydropower production. As can be seen in the figure, high levels of spill occur during time periods with high production which follows from the hydrological coupling as explained in section 3.1.2. Transformed to energy, the spill constitutes 0.03 and 0.13 TWh respectively, or 0.2 % and 0.8 % of the annual hydropower production. Although water spill increases significantly as more intermittent production is integrated with the power system, the resulting energy losses remain relatively small. This again points out the flexibility of the simulated hydropower system; even at high shares of intermittent production the hydropower is able to balance most of the variations in residual load with only small effects on annual production losses.

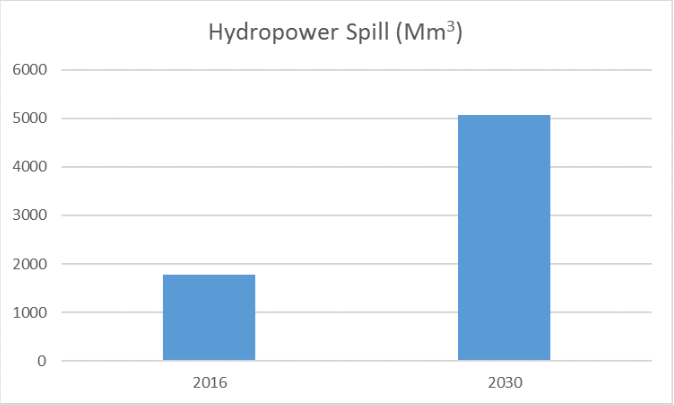

Figure 15: Annual water spill in 2016 and 2030 for the detailed model.

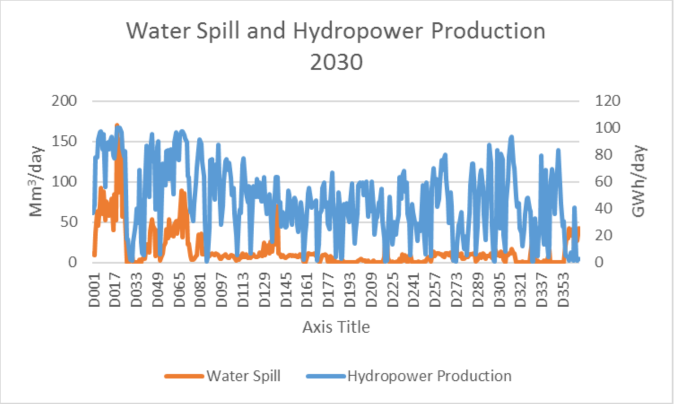

Figure 16: Daily water spill and hydropower production during 2030 for the detailed model.

6.4 Optimization with Additional Margins for Unexpected Decreases in Wind Power Production

So far, the results of the detailed model have been computed under the assumption of perfect forecasts. This means that hydropower scheduling is conducted with perfect information about future hydrological and meteorological conditions and that the available water resources are optimally distributed across the year. It also means that the production levels of the power generation technologies are determined without considering the occurences of unexpected production increases and decreases caused by forecast errors of intermittent production. In reality, the power system needs to be able to deal with such occurences and in order to do this sufficent amounts of flexible power generation capacity and resources have to be provided, either through stand-by production and consumption technologies or by maintaining larger production margins in generating power production facilities.

To get an idea of how larger production margins on hydropower affect the balancing capability the system is also optimized in a case where additional margin requirements on hydropower for unexpected decreases in wind power production levels are enforced by including restrictions (13) and (14). The installed power generation capacity in 2016 and 2030 for the detailed model with and without additional production margins are shown in figure 17. For the model with margins, installed wind power capacity in 2030 decreases by more than 15% compared to without, and CHP and peak capacity increases from 774 MW and 2241 MW to 1455 MW and 2464 MW respectively. Figure 18 displays the generated power per production technology. For the model with margins, wind power production in 2030 decreases by around 3 TWh, which is mainly replaced by production from CHP. Peak generation in 2030 also increases from 0.27 TWh to 0.49 TWh.

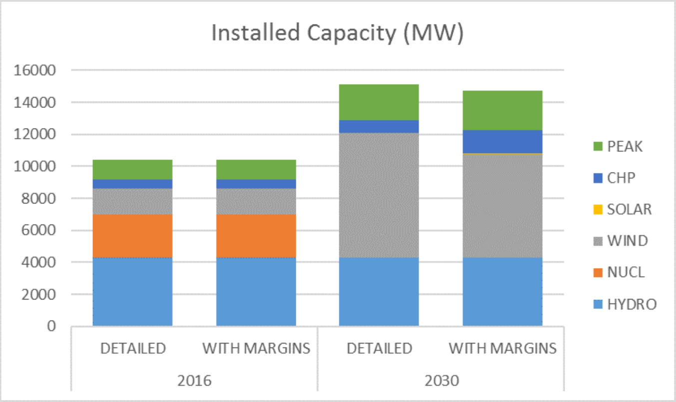

Figure 17: Installed power generation capacity in 2016 and 2030 for the detailed model with and without additional production margins.

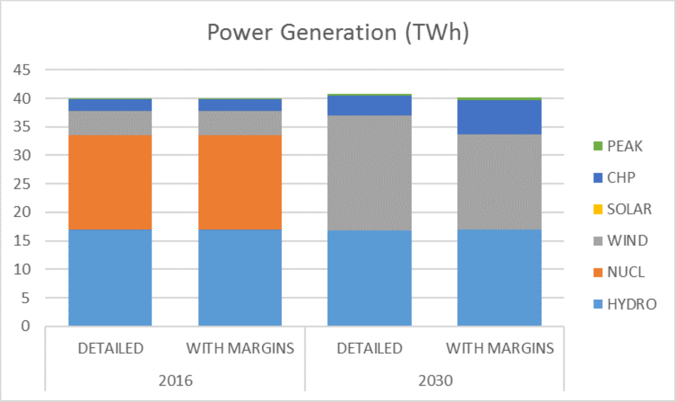

Figure 18: Annual power generation per production technology in 2016 and 2030 for the detailed model with and without additional production margins.

The results show that enforcing additional production margins for unexpected wind production shortfalls significantly impacts the extent of wind power integration. This follows directly from the significance of available capacity when it comes to the hydropower system's balancing capability. It should be noted that restricting hydropower to be able to balance all of the production decreases in 95% of the cases is not necessarily the optimal way of ensuring system stability. For instance, it might be more cost-effective to allow lower production margins and to a larger extent utilize peak generation capacity to balance the unexpected production reductions. Either way, the results suggest that the difficulties of dealing with forecast errors significantly impact the optimal investments in the power system. They also highlight the significance of the development of methods to deal with such difficulties, including both flexible power production and consumption options and improvements of forecasts.

7 Discussion

7.1 Developing a TIMES Model Capturing the Technical, Physical, Legal and Market Related Restrictions of Hydropower

This thesis is to a large extent focused on the development of a TIMES model which better capture the technical, physical, legal and market related restrictions of hydropower. The following section is divided into two parts which discuss the areas where the developed model could be improved. Firstly, the limitations of the model are described and the implications on the model results are estimated. Thereafter, a short discussion follows of how the model could be improved to better capture the characteristics of intermittent and hydropower production.

7.1.1 Sources of Errors

Simple Representation of Hydropower Plants
The representation of the technical restrictions of the hydropower plants is limited to installed capacities and single production factors for each plant, and the model does not account for prohibited production levels or the efficiency's dependency on water flow and head. According to (Amelin 2009), these factors probably only have a marginal impact on hydropower's regulating capability. An increase in intermittent production might, however, lead to a decrease of the total hydropower production if the power plants are increasingly operated at non-optimal production levels. In (Lönnberg 2014) the hydropower production of the Lule-River is simulated over 21 days and the efficiency's dependency on water flow and head as well as prohibited production levels are accounted for. In the case of high wind penetration levels (20 000 MW nationally), the power production per m^3 water used decreases by 2% compared to today's wind penetration levels. If the efficiency was to have a similar impact on the annual production of the studied system, the annual hydropower production in 2030 would decrease by approximately 0.30 TWh, which would have to be delivered from elsewhere. It would also be of particular interest to study the extent to which the hydropower plants are able to operate at high production levels, since the available capacity is shown to have a significant impact on the regulating capability.

Perfect Forecasts of Intermittent Production and Natural Inflows
Probably the most severe simplification of the model is the assumption of perfect forecasts of intermittent production and natural inflows to hydropower reservoirs. The unpredictability of these entities impacts the system on all time-scales from hours to years and impacts hydropower scheduling both when it comes to the optimal utilization of water resources and the maximal and minimal production levels of the system.

At shorter time-frames the assumption of perfect forecasts enables the modeled hydropower system to perfectly plan its production and reservoir water levels in order to follow the load variations. For the real system, the water resources might not be as perfectly coordinated and increased spilling might become necessary in order to meet an increasingly varying and unpredictable demand. In (Lönnberg 2014) the system is simulated one day at a time and each day is optimized with false information about future wind production patterns. Even at high levels of wind penetration the amount of spill remains small, which indicates that the short-term unpredictability of wind production does not have a significant impact on the operation of the hydropower system. Maybe more importantly, the unpredictability of intermittent power production may also place additional margin requirements on hydropower. This is not accounted for by the model since the hydropower demand is exactly known in each time-slice. In one case, production restrictions are implemented explicitly in order to get an idea of how larger production margins impact the balancing capability. The results show that the impact is significant. However, in the studied case it is assumed that hydropower alone should be able to balance all of the production reductions in 95 % of the cases, and the solution is therefore not necessarily optimal. For instance, it might be more cost-effective to place lower margin requirements on hydropower and to a larger extent utilize peak generation to balance the production reductions caused by forecast errors. To find such an optimal solution a stochastic approach is necessary.

At longer time-frames the assumption of perfect forecasts leads to an optimal utilization of the annual amount of available water resources (as defined by natural inflows and the specified water levels at day 1 and 365). Hence the hydropower will, for example, produce at extra high levels during spring if it is known that the demand during winter will be sparse. This might lead to an overestimation of the annual hydropower production. With the same amount of available water, the annual hydropower production during 2016 for the model exceeds the real production of 2012 by ca. 2%. This indicates that for today's power system any overestimation of the annual production is relatively small. An increased share of intermittent production probably makes long-term forecasting of the hydropower demand more difficult due to the seasonal uncertainty of intermittent production, which might in turn lead to a less optimal utilization of water resources. Exactly how and to what extent this impacts the annual production is, however, difficult to tell.

The uncertainty of the magnitudes of seasonal and annual production levels and inflows also impact the optimal power system due to the possible occurrences of longer periods with particular low intermittent and hydropower production. Since the natural inflows and solar and wind availabilities are given for single years this is not accounted for by the model. Accounting for the seasonal and annual uncertainty may increase the cost-effectiveness of predictable power generation since it is able to generate power independently of the natural conditions.

Variability Within 4 Hours

Since the time-steps of the model are 4 hours long the model does not account for the variability of intermittent production within 4 hours. For wind, which constitutes the vast majority of the predicted intermittent production, the variability at time-scales of 4 hours or longer is significantly bigger than at smaller time-scales (Holttinen et al. 2009), and the model therefore captures the most significant variations. If solar or other intermittent production were to make up significant shares of the production, it might be necessary to take the variability within 4 hours into closer consideration.

Smoothing Effect
In the model, the variability of wind and solar power production are described by time-slice specific availability factors which are calculated from the production levels and installed capacities of 2016. Hence, the smoothing effect, i.e. the decrease in variations due to an increased installed capacity, is not accounted for by the model. For the studied system the investment decisions are primarily affected by the number of occasions during which intermittent production is at low levels. Since the smoothing effect is primarily effective on small time-scales the neglectance of the smoothing effect therefore probably does not have a major impact on the results. It would be of interest, however, to further investigate how increased capacity installments impact intermittent production variability, and especially how it affect the number of occasions with low production levels.

7.1.2 Improvements

To increase the number of conclusions that can be drawn and the generalizability of the results the model would need to be expanded to include more hydropower systems, a wider range of production technologies and representations of electricity transmission and import/export. This could be done fairly easily within the TIMES framework and the biggest challenges of expanding the model would probably consist of time and other resources to collect the necessary data.

It would also be of interest to, at least for a smaller system, improve the representation of the technical restrictions of the power plants in order to see how this would impact the model results. In TIMES, such a representation is limited by TIMES's requirement of linear formulations; however, by describing each power plant by several processes and making use of the basic unit commitment features of TIMES (described in (Panos & Lehtilä 2016)) it should be possible to increase the level of detail significantly. Again, the biggest challenges would probably concern data collection.

The most difficult task when it comes to improving the model is to better describe the uncertainties of intermittent production and natural inflows to hydropower reservoirs. TIMES is originally a tool for developing deterministic models, i.e. models in which no randomness is involved in the development of future states of the system. The possibilities of explicitly including the randomness of the uncertain parameters are therefore limited. Lately, there has been an increased interest in these questions and some stochastic features have become available in TIMES (see (Loulou & Lehtilä 2016)). These features have for example been applied in (Seljom % Tomasgard 2015) and (Seljom % Tomasgard 2017) to study the effects of wind, solar and hydro uncertainty on the development of Nordic power systems. However, the possibility to include stochastic features in TIMES is currently limited to only impact investment decisions, and the operational decisions within the year are still optimized deterministically. Although it is possible to capture the advantages of predictable power generation due to the uncertainty of seasonal and annual production levels, it is as of today not possible to describe how the uncertainties impact the operation of the power system. Furthermore, a stochastic representation of intermittent production and natural inflow uncertainty is also complicated by:

- The high number of time-slices in the model. Stochastic modeling is very computationally demanding. To include a stochastic representation of the uncertainties would therefore probably imply that a lower temporal resolution would become necessary. This in turn would mean that an explicit description of hydropower water levels and the variability of intermittent production would not be possible. There seemingly exists a trade-off between an explicit representation of uncertainties and detailed descriptions of intermittent production variability and hydropower flexibility.
- The difficulty of accounting for the value of weather forecasting. If it becomes possible to describe how the uncertainties impact the operation of the power system, the value of forecasting should also be represented or else the flexibility of the system would be undermined. This further increases the difficulty of modeling the system.

An improved representation of intermittent production and inflow uncertainty would therefore require further development of existing TIMES or methods to combine the insights from models acting on different temporal and spatial levels of detail.

7.2 Representation of the Variability of Intermittent Power Production and Flexibility of Hydropower in Long-Term Energy System Models

Comparing the results of the simple and detailed models it can be seen that the simple model predicts lower investments in and production of CHP and peak generation, which can be explained by the model's inability to account for the increased number of situations with a high power demand and low intermittent production availability. This suggests that energy system models with a low temporal resolution, by not accounting for these occasions, overestimate the power systems ability to balance an increased share of power generation from intermittent sources.

The results of the detailed model suggest that the flexibility of the studied hydropower system is primarily restricted by the available power production capacity rather than reservoir volumes or the hydrological coupling and water usage regulations of the river. The simple model's overestimation of the power system's flexibility can thus not be explained by an overestimation of the flexibility of the hydropower system, but rather by the overestimation of the flexibility of other power generation technologies or, put another way, the underestimation of the balancing requirements of intermittent production. If anything, the simple representation of hydropower leads to an underestimation of hydropower flexibility due to the assumption of low availability during peak time-slices. This, however, has a relatively small effect on the power system's optimal composition compared to the overall overestimation of the power system's flexibility.

In the case where additional margin requirements on hydropower are enforced the installed wind capacity in 2030 decreases by 15 %. Even though the computed solution is not necessarily the optimal way of ensuring system stability, this points out the importance of considering the power system's ability to balance unexpected production decreases due to forecast errors. If long-term energy system models are applied on power systems with high shares of intermittent power production, the inclusion of these issues needs to be given more attention.

The desirable level of detail in long-term energy system models depends on the objectives of the model. In a model like TIMES-Sweden, which includes vast descriptions of energy sectors and technology options, a high temporal resolution may not be desirable due to the negative effects on data-handling, computational time and transparency. Within the framework of a lower temporal resolution some improvements can still be made. For example, the results suggest that a lower peak factor of wind production would probably describe the system more accurately, since a number of occasions with a high demand and low wind availability occur during the winter. Furthermore, it could, if possible, be beneficial to adjust the peak time-slices to represent hours with peaking residual load rather than electricity demand, since these hours more accurately describe situations with high requirements on system flexibility.

To more accurately describe the variability of intermittent production and flexibility of hydropower a higher temporal resolution is necessary. In this thesis an implementation of one such model has been carried out. The work that has been performed illustrates the capability of long-term energy systems models to capture the variability of intermittent production in greater detail and the characteristics governing the flexibility of hydropower. It also, however, highlights the difficulties of capturing the uncertainties related to intermittent energy sources and inflows to reservoirs. Further work concerning the development of models or methods to better represent these uncertainties is necessary.

The fact that the hydropower system is primarily restricted by available capacity suggests that the hydropower system could be described fairly accuratley by the total installed capacity and resevoir volume only. This could significantly simplify an expansion of the model since data for individual plants and river systems would not have to be collected. However, to confirm this conclusion other river systems and hydrological and meteorological years would have to be investigated.

7.3 Swedish Hydropower's Capability of Balancing Production Variations

The results of the detailed modelshow that the simulated hydropower system is very flexible in following variations in residual load. In the case study, the hydropower of the Lule River is able to balance most of the variations from an increase of intermittent production capacity to 7790 MW, an increase by over 370 %. In 2030, the production from intermittent energy sources makes up ca. 50 % of the annual power production. The hydropower system's capability of balancing intermittent production is primarily restricted by the available power production capacity rather than reservoir volumes or the hydrological coupling and water usage regulations of the river. To draw any conclusions for the whole of Sweden the study would have to be expanded to include more hydropower systems and investigate additional years of hydrological and meteorological data. However, the results do indicate that the biggest challenges of balancing high shares of intermittent production with hydropower probably do not concern the hydropower system's ability to follow the increasing variability in residual load, but rather other limitations such as transmission capacities or restrictions stemming from production uncertainties.

From a system perspective, the integration of intermittent production is not significantly restricted by any continuous balancing requirements due to the flexibility of the studied hydropower system. Rather the integration is restricted by the occurence of particular situations with high power demands combined with low intermittent production availabilities. In 2030, peak generation produces 0.27 TWH, or 0.7% of the total annual production. This can be compared to the share of condensing power during the period 2010-2015, which was below 0.05%. In the model, peak generation is assumed to be provided from a gas turbine peak device fueled by relatively expensive biogas. In reality, there exist several other possibilities for meeting peak demands, including flexible consumption, electricity import and increased flexibility of CHP. To get a more general description of the possibility of integrating intermittent production, the study would have to be expanded to include these options.

8 Conclusions

The aim of this thesis has been to investigate how a present national TIMES model can be improved to better capture the technical, physical, legal and market related restrictions of hydropower. In order to do this, a TIMES model has been developed that explicitly accounts for the installed capacities and production factors of individual hydropower plants and the hydrological coupling, natural inflows and water usage regulations of the Lule River. The development of the model suggests that the biggest challenges of accurately describing the flexibility of hydropower consist of time and resources for data collection and the difficulty of capturing the uncertainty of intermittent production and inflows to hydropower reservoirs.

The developed model has also been compared to a model which mimics the temporal resolution and hydropower representation of the conventional long-term system model TIMES-Sweden. The results indicate that models with lower temporal resolution overestimate the power system's ability to balance an increased share of power generation from intermittent sources due to the models' inability to account for the increased occurrences of situations with a high power demand and low intermittent production availability. When it comes to improving the models to more accurately describe the variability and flexibility of the system, it is therefore primarily important to develop the models to better account for these occasions. The results also highlight the importance of accounting for the power systems ability to balance unexpected production decreases due to forecast errors of intermittent production.

When it comes to estimating the Swedish hydropower's flexibility the scope of the case study limits the number of conclusions than can be drawn. However, the results do indicate that the biggest challenges of balancing high shares of intermittent production with hydropower probably do not concern the hydropower system's ability to follow the increasing variability in residual load, but rather other limitations such as transmission capacities or restrictions stemming from production uncertainties.

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