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Report

European power market analyses to be carried out within FME ZEN

ZEN deliverable D5.3.1 for 2017

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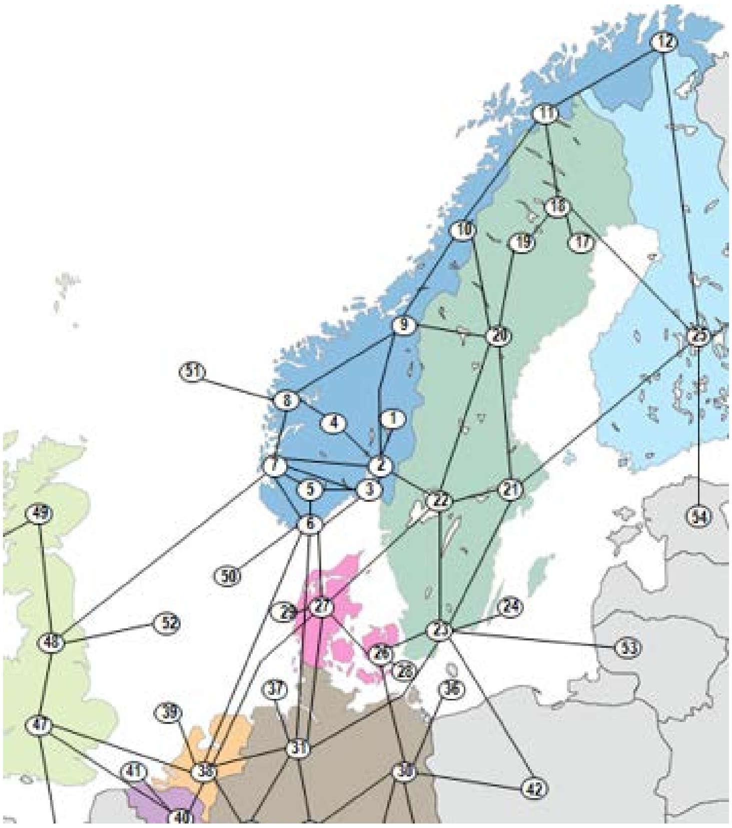

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ABSTRACT
Local energy solutions such as the utilization of local renewable energy resources, and increased energy efficiency, are important for being able to reduce European greenhouse gas emissions to amounts that are in line e.g. with a 2 degree global warming. In the long run, emission levels are affected by many factors including energy system operations, investment decisions, policy instruments, social acceptance for environmental policy, amongst others. Thus, it is not trivial to calculate the full impacts of e.g. 1 TWh extra renewable energy produced locally. Still, it is possible to elaborate on and reveal important mechanisms, which will increase our understanding of those. This report present a plan for European power market studies to be carried out within the FME ZEN. The overall intention with the planned studies is not to provide more accurate numerical calculations than in previous studies, but rather to show how numerical results are affected by which economic mechanisms that are included in such studies. Thus, the studies shall be a basis for creating increased mutual understanding of arguments within FME ZEN.

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1 INTRODUCTION

1.1 Background

This report is developed within task 5.3 of FME ZEN [1]. It is deliverable D5.3.1 for 2017 [2]. Task 5.3 and deliverable D5.3.1 are described in Box 1.1 and Box 1.2 respectively.

Box 1.1. Task 5.3: Energy system impacts.

Reduced electricity consumption because of ZENs will lead to lower GHG emissions when parts of the corresponding decrease in power generation comes in fossil fuel power plants. Also, the extra flexibility provided by ZEN reduces the need for investing in other flexibility options. In this task we will apply state of the art electricity market models of the Nordic and North-European power system to study the impact of ZEN in a set of scenarios. The goal of the task is to show how ZEN affects CO2-emissions, power prices, and reduces the needs for investments in new generation and flexibility such as transmission lines. The saved long-term costs of for the overall power system will also be calculated. This task provides important input for WP2 in terms of detailed modelling of operation of the national and European power system and markets and how this can be affected by policy and technology choice in ZEN. It also provides inputs to the local energy system optimization in WP5 by calculating how reduced power consumption affects CO2-emissions from the power system in different scenarios.

Box 1.2. Deliverable D5.3.1: Designing a power system analysis strategy for ZEN.

Objective: A strategy for how to carry out power system analysis and assessment of environmental impacts within ZEN will be developed. **Why this work is important for ZEN:** Traditionally there have been different views about environmental impacts of e.g. reduced electricity consumption. At the same time, this is an important question for assessments that will be carried out within ZEN. It would therefore be beneficial to establish a consensus about this within the ZEN consortium. A first important step to achieve this, is to build a common scientific basis to base further discussions upon. The different views and important perspectives must therefore be represented in the set of cases that are set-up to be analyzed quantitatively.

1.2 WP1 work on ZEN definitions and metrics

Within WP1, a task dealing with ZEN definitions and metrics [3] has started. One of the issues that has been discussed in the corresponding workshops is the measurement of benefits of local environmental friendly energy solutions. One possibility is to shift from the measurement of CO_2 impacts (the approach of the former FME ZEB – which requires an estimate for a CO_2 factor on electricity consumption), to a multi-criteria approach. However, the definition work in WP1 does not reduce the need to reach a common scientifically based understanding within FME ZEN on the environmental benefits of local energy solution in Europe. The energy system studies carried out in WP5 are therefore expected to provide important inputs for the further work in FME ZEN.

1.3 Purpose of this report and the planned studies

Purpose of report
This report outlines a plan for the initial European power market studies to be carried out within WP5. The report will be a supporting documentation to the planned partner workshop 22. June 2017. The plan will then be adjusted on basis of the outcome and discussions of the workshop.

Purpose of planned studies
For the planned studies, we will use state of the art model and dataset for European power market simulations. The overall intention with the planned work is, however, not to provide more accurate numerical calculations than in studies that have been published before. Our goal is rather to elaborate on the different mechanisms that can be taken in such studies, and to show how the inclusion of those mechanisms inevitable will affect the calculated impacts of environmental friendly local solutions on European CO_2 emissions. For instance, reduced electricity consumption will give a very different result in a marginal operational analysis (reduced thermal power generation, and reduced emissions), than in an analysis that takes the European emission permit market into account (no impacts on emissions). More specifically our goal is to:

- **Represent** the most important views held and perspectives taken (i.a. among partners in FME ZEN, both industry partners and research partners) in the set-up of the cases we study.
- **Reveal** how the different perspectives affects simulation results, among other things on the calculated impacts on European CO_2 emissions due to local energy solutions (renewables, energy efficiency).
- **Consistently compare** different cases by utilizing the same model and dataset for the different cases.
- **Explain** the involved mechanisms, i.e. why results become different.

Further goals will be to publish findings, specify new targeted studies for ZEN, and – most importantly – to utilize knowledge gained in the process together with partners to reach a common understanding about the main mechanisms involved.

1.4 Structure of report

A short outline of the different views to be represented by scenarios is described in Chapter 2. In Chapter 3 we describe the methodology, including the applied model for analysing the European power system, input data types, selection of reference scenario, representation of local energy solutions in aggregated models, scenarios to be analysed, which simulation results we will focus on, and more. Conclusions are provided in Chapter 4, including a summary, a discussion of next steps in the development of the plan for power market studies to be carried out, as well as initial thoughts on further work.

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2 SHORT OUTLINE OF VIEWS TO BE REPRESENTED

2.1 Traditional approach: Marginal analysis

There is a long tradition for calculating how a specific marginal change affects the total European power system. Such analyses are typical carried out for a given state of the system, say 2030. All assumptions regarding power system inputs (capacities for generation technologies / transmission cables, amounts of renewable generation, consumption, fuel-prices etc.), are then taken from an external forecasts (e.g. ENTSO-E and Statnett). For the forecasted power system, the impacts of one particular change (e.g. 1 TWh extra renewable generation in Norway) is then studied. Two analysis are carried out: One reference scenario without the considered change, and one alternative scenario with the considered change implemented. All differences in simulation results between those two scenarios are then the impacts of the change under consideration.

There are many examples of this kind of studies, including studies of new cables, new power generation, changes in electricity demand, and changes in fuel- or CO_2-prices. Figure 2.1 shows examples of such calculations that has been carried out by SINTEF Energy Research, and that focuses on the impacts on CO_2 emissions, cf. [5].

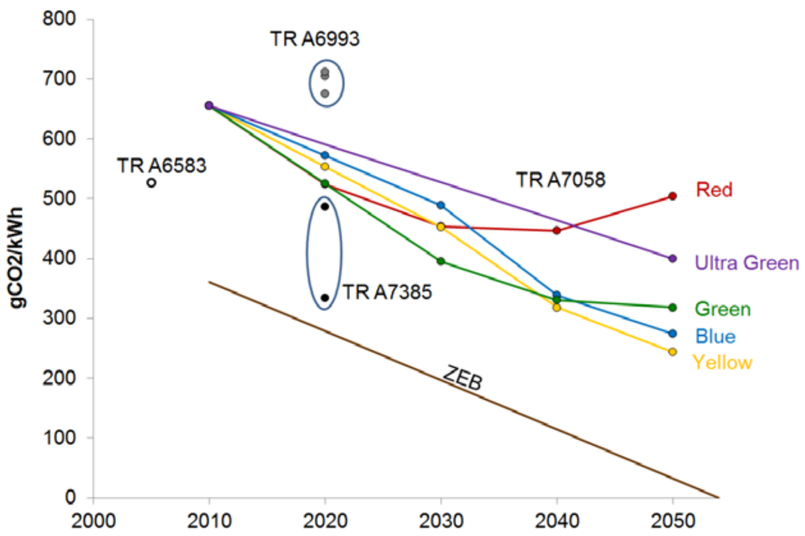


Figure 2.1 Examples of CO_2 impact studies carried out by SINTEF

In general, it is not easy to forecast far into the future. Therefore, it is far from trivial to calculate the impacts of a given change. There are several approaches to deal with uncertainties about the future. Often, a set of future *scenarios* is developed. The scenarios are often different in several perspectives, and exhibit an internal consistency through a qualitative story-line for the future development. See for instance the difference between Red, Green, Blue, Yellow and Ultra Green described in [4], and corresponding results in Figure 2.1. Another strategy is to change one single parameter at the time to study the impact of that particular uncertainty, a *sensitivity analysis*. Such a study is carried out for a set of values for the uncertain parameter.

2.2 ZEB approach: Average values

For a given scenario, average emissions (e.g. tCO_2/MWh) can be calculated by dividing total emissions from electricity generation (tCO_2) by total electricity generation (MWh). FME ZEB utilized such average values instead of the marginal values [6]. See [4] for a documentation of the ZEB emission coefficient curve in Figure 2.1. As a comparison, emissions from gas-power generation is typically somewhat below 400 gCO2/kWh.

In the marginal analysis, only those units that have marginal cost very close to the initial equilibrium (before the considered change) will affect the calculations. Thus, results become sensitive towards small changes in the assumptions. Average values are less sensitive to small change in assumptions, and possibly easier to understand. It can also be argued that they to some degree represent the long-term impacts in the power system, cf. Chapter 2.3.

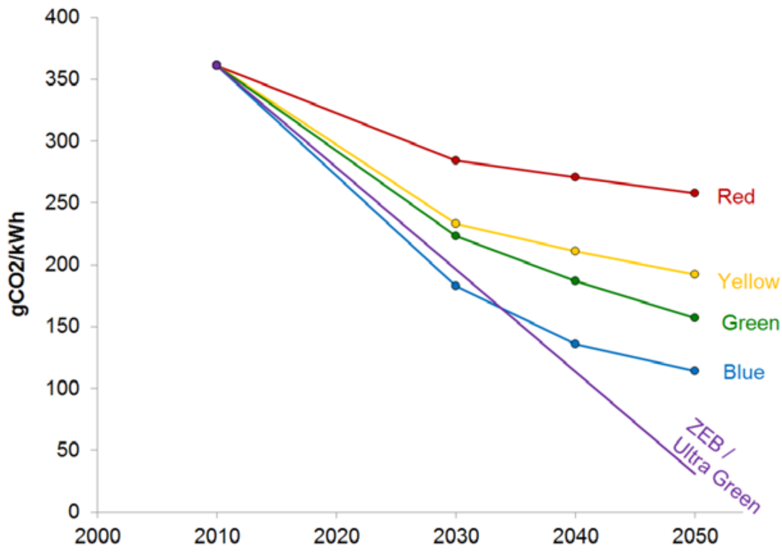


Figure 2.2 Average emissions for scenarios reported in [4]

2.3 Improving the traditional approach: Long term impacts

This approach is similar to the marginal analysis as the impacts of a given change is evaluated. However, the analysis is extended by also considering the effect on system development, i.e. on installed capacities for generation and transmission. Optimal investments in new capacities for different generation technologies and transmission capacities are calculated, as well as retirement of existing capacity due to aging and/or to avoid maintenance costs for mostly unused units. See for instance [7] for a study that includes optimal operation dispatch and optimal capacity change, among other things.

The investment module algorithm of the EMPS model is illustrated in Figure 2.3. Basically, it determines a Nash equilibrium for investments in generation and transmission. A first it evaluates simulated prices before any investments, then it phases-in some of the profitable capacity, and then the operational model is run again to calculate new prices. This process continues until all profitable investments are included, and all included investments are profitable.

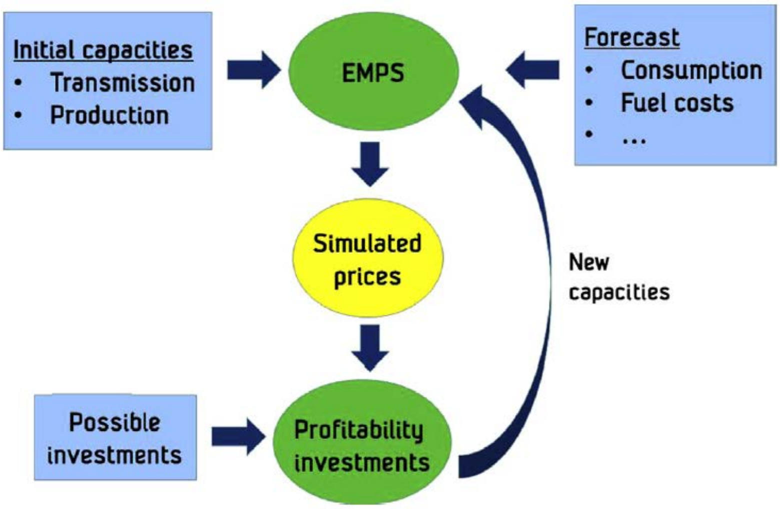


Figure 2.3 Investment module algorithm in EMPS model

A disadvantage with this traditional marginal analysis is that it only considers the operation of a given system in a given future year. It does not account for impacts on the system itself. Consider for instance the impacts of reduced demand. Over time, a reduction in demand will lead to lower power prices, and thus affecting the both investments in new generation capacities and retirement of existing capacities. In principle, reduced demand can therefore primarily lead to less wind- and solar-power generation. In a traditional marginal analysis, however, only operation costs are minimized. Since the marginal costs for wind- and solar-power generation are close to zero, no operational costs are saved by cutting back their generation. Thus, reduced demand will lead to a corresponding reduction in thermal power generation.

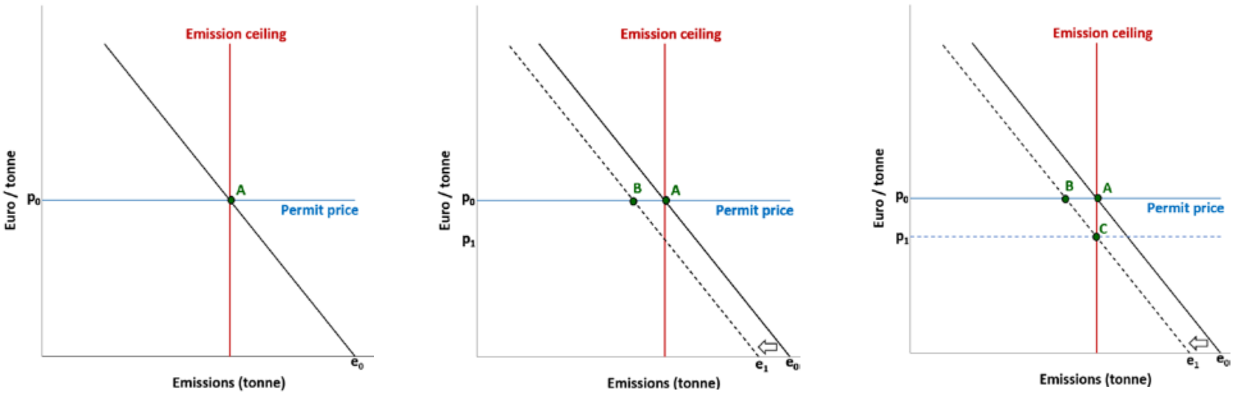
For the special case of an unchanged electricity generation mix (i.e. reduced demand give a proportionally reduction for all electricity generation types), the study of the long-term impacts would lead to the same result as average emission / ZEB approach. Thus, the ZEB approach could be interpreted as a simplified methodology for taking into account the long term impacts on the development of the power system.

2.4 Economists' view: Emission permit market

In an emission permit market (also called cap-and-trade market), the total emitted amount of greenhouse gases from the emitting sources included in the system, is predefined by the number of emission permits in the system. Emissions from Europe's power generation are included in such a system: the EU Emission Trading System (EU-ETS). The impacts of EU-ETS can be accounted for in power market models e.g. running the model iteratively with different emission costs, until the emitted amount in total is on the emission ceiling.

The effect of this mechanism is that other measures taken to reduce emissions (of those included in the system), such as reduced demand and/or increased renewable power generation, have no impact on total emissions. This is illustrated in Figure 2.4. However, there will be effects on other factors, e.g. on power prices, the costs of environmental policy, and permit prices.

The initial equilibrium in the emission permit market is illustrated in panel (a). The black curve shows the willingness to pay for emission permits. The curve is downward-sloping because a high price for permits will lead to a low demand for permits, and vice versa. If the emission permit price is zero (equivalent to no permit market), the emitted amount is e_0. The number of permits in the system is given by the red vertical line. Thus, the market equilibrium is given by "A", whereas the equilibrium price is p_0.



(a) (b) (c)

Figure 2.4 Impacts of reduced electricity demand within the EU ETS market

Now, we assume a reduction in the electricity demand. As a consequence power prices goes down (not illustrated here), and thus the willingness to pay for emission permits to fossil fuel power generation falls as well. In other words, the curve showing the willingness to pay for emission permits shifts inwards. This is illustrated in panel (b). If there would not exist a permit market, the emission level would be reduced from e_0 to e_1. If the emission permit price had been constant, the emitted amount would be reduced from "A" to "B". The move from "A" to "B" is a representation of the mechanism accounted for in the marginal analysis approach, cf. 2.1. However, "B" is not a market equilibrium since there is an excess supply of emission permits. Consequently, permit prices are reduced until a new equilibrium is restored at "C". This is illustrated in panel (c). In the new equilibrium, the emission permit price has been reduced from p_0 to p_1, whereas the emitted amount is unaffected (same value in "A" and "C").

2.5 A synthesis: Adaptive policy-making

There exist no emission permit ceiling defined for EU ETS up to 2050 yet. Furthermore, if such ceiling had been defined, there would not be a guarantee that policy makers would not change it again before 2050. The economic and regulatory instruments used to reduce CO_2 emissions can also evolve in time, e.g. from emission permits to emission taxes, or to technology regulation. However, measures that reduce the cost of CO_2 mitigation, or push the energy system in an environmental friendly direction, make it simpler for future policy makers to implement ambitious environmental policy, e.g. through the reduction of the number of permits in within EU ETS. Even though this mechanism obviously exists, it is far from trivial to estimate, and it would be even harder to test them empirically.[1]

[1] Another question is which assumptions are needed in a standard economic model (e.g. in micro-economy or game-theory) to get this mechanism as a result. So far, we have not planned literature review or economic modelling in this direction within FME ZEN. In the following, we take it as a premise that this mechanism exists.

It is however possible to *illustrate* such a mechanism by replacing the vertical emission permit constraint by a curve that represents policy-makers' ability to agree on emission reductions, cf. the red curve in Figure 2.5. The curve is upward-sloping as low emission permit prices promote more ambitions policies over time, and vice versa.

As the red curve crosses "A", this represent an equilibrium also with respect to the emission ceiling. However, with the reduced demand, policy makers are able to agree on lowering the emission ceiling (by the horizontal distance between "A" and "D"). At "D", the emission permit price is lower, but the emitted amount is also lower. To illustrate this impact in the power market simulations, a first estimation of the equilibrium point "D" could be an emission permit price $(p_0 + p_1) / 2$.

Figure 2.5 Impacts of reduced electricity demand within the EU ETS market

2.6 Other scenarios

The scenarios described so far represent different approaches for calculating environmental benefits of reduced demand and / or local generation. In the following, we will still describe a few other scenarios that are of high relevance within WP5 from slightly different perspectives.

Cost-effective local energy solutions
By definition, cost-effective solutions for reduced demand, flexibility, and local generation must be fully utilized in a socio-economic optimal solution. If not, there will be a welfare loss for society. Moreover, if markets are well-functioning, cost-effective local solutions will be profitable for investors. Based on forecasts and sensitivities regarding the cost development of local solution compared to alternative solutions, the welfare loss of not utilizing them, and the profitability of utilizing them under efficient market pricing, can be calculated.

General equilibrium effects
Whereas partial models are models for a single market, e.g. the day-ahead market for electricity, other models include several products or even all products based on some categorization (this is the case for so-called general equilibrium models). In this report, we have briefly discussed how an analysis can be set-up for an electricity market model to include interaction with the emission permit market. However, in principle there will also be interactions with all other markets. Some of the most relevant are the markets for fuels to

electricity production, especially natural gas, coal, and biomass. Those interactions can be calculated by using models that includes several markets. Furthermore, general equilibrium models typically have an explicit modelling of consumers' optimization, which can be utilized when carrying out studies of substitution effects between electricity and other commodities.

3 METHOD OF CALCULATION

3.1 Calculator: EMPS model

In Task 5.3, we will apply state of the art electricity market models of the Nordic and North-European power market. To be able to consistently compare different cases by utilizing the same model and dataset for the different cases, we will use SINTEF Energy Research's EMPS model (no: Samkjøringsmodellen) for most scenarios mentioned in this report. However, it can be expected that additional energy system analyses beyond those mentioned in this report will be carried out in Task 5.3 later, and by students at NTNU. A description of the EMPS model is included in Appendix A. See also [8] and [9] for short descriptions of the operational model and investment functionality respectively.

3.2 Dataset – the inputs

European datasets for the EMPS model have been developed in several former and ongoing research projects, funded by the industry, the Norwegian Research Council, and the EU. National and international research partners and industry is also cooperating in the development of the datasets, and some (such as Statnett, NVE and the large hydropower producers in the Nordic area) have their own datasets for the EMPS model, and for other hydropower optimization tools developed by SINTEF Energy Research. A dataset to the EMPS model include many different elements, such as (list is not exhaustive):

- Hydropower: Detailed description of the production system in specific water courses, including reservoir sizes, generation capacity and its location in the water course, efficiencies, waterways, inflow data for different climate years, and environmental constraints. Typically, there is a more detailed description for Norway and Sweden than for other countries.
- Thermal power (fossil fuel, nuclear and bio) units: Generation capacity (MW), availability, efficiencies, fuel-types, emission coefficients, and start-up costs. For all modelled units, sometimes aggregated categories of them.
- Fuel prices (e.g. natural gas, coal types, biomass), and CO_2 price. Sometimes marginal costs are specified directly.
- Variable renewable generation (e.g. solar-power and wind-power): Amounts e.g. hour by hour for a set of climate years, for each technology and area.
- Transmission capacities between different areas in the model (onshore and offshore cables). Some countries are divided into several areas with corresponding transmission constraints between them, whereas some are represented by a single node. This varies between different datasets. Within-area power transmission is often not taken into account, but can be included.
- Demand: Annual demand, within-year profiles, temperature sensitivity, price-flexibility. Several demand types with corresponding characteristics can be specified for each area. Gradual adjustment to power prices can be included.
- For investment analysis (when included): Investment costs, interest rates, retirement due to aging, maintenance costs. This can be specified for all capacities, and for all investment options.

Since the development of the EMPS model and datasets in an ongoing process, it is beneficial to postpone the final decision for which dataset we will use. However, in the following we will give a brief description of e-Highway2050 [10] scenarios, which is one of the most promising alternatives currently. Other possible datasets include (but is not limited to): a dataset under construction for the project Norwegian Energy

Roadmap 2050 (see e.g. description in [12]), Norstrat dataset for 2050 [13], Twenties [14] dataset for 2030, and Susplan [15].

The e-Highway2050 project was funded within the 7th EU framework program. It had 28 European partners, also including ENTSO-E, national TSOs, Eurelectric, and SINTEF. One of the results was a plan for pan-European grid architecture, based on various future power system scenarios. Some of the scenarios that were studied are described in Box 3.1. There already exist datasets to the EMPS model for some of the e-Highway scenarios, whereas they can be constructed for the others.

Box 3.1. Selected e-Highway scenarios for 2050 [11].

- **X-5: Large scale RES**: focus on the deployment of large-scale RES technologies. A high priority is given to centralised storage solutions accompanying large-scale RES deployment.

  Large scale RES

- **X-7: 100% RES electricity:** 100% based on renewable energy, with both large-scale and small-scale, links with North Africa. Thus, both large-scale storage technologies and small-scale storage technologies are needed to balance the variability in renewable generation.

  100% RES el.

- **X-10: High GDP growth and market-based energy policies**: Internal EU market, EU wide security of supply and coordinated use of interconnectors for cross-border flows and exchanges in EU. CCS technology is assumed mature.

  Big and market

- **X-13: Large fossil fuel deployment with CCS and nuclear electricity:** electrification of transport, heating and industry is considered to occur mainly at centralised (large scale) level. No flexibility is needed since variable generation from photovoltaic (PV) and wind is low.

  Large fossil fuel

- **X-16: Small and local:** The focus is on local solutions dealing with decentralised generation and storage and smart grid solutions mainly at distribution level.

  Small and local

3.3 Representation of local measures

<u>Impacts of reduced demand</u>

Many energy system analyses are so-called contractual or what-if studies. Starting from a reference scenario, e.g. one of those mentioned in Box 3.1, the following can be investigated: What is the impact of changing the value of a specific parameter? As an example, consider the calculation process described in [4]:

> "The marginal emissions in the different scenarios are the marginal changes in emissions in Europe as a consequence of changes in the demand of 1 TWh in Norway. The following methodology is used to calculate the emissions: 1) The demand in Norway is increased with 1 TWh/year distributed proportionately over all load periods in a year; 2) EMPS is run with and without this increase in demand; 3) Differences in energy production show how the increased demand is covered in each time period, and the corresponding changes in emissions are calculated."

The work described in [4] – which was the basis for the ZEB emission curve – calculated the impacts of a proportional change of 1 TWh / year in the Norwegian electricity consumption. Impacts of changed electricity consumption is also a natural starting point for the energy system analysis to be carried out within FME ZEN. However, the scenarios will be considerably different, cf. the discussion in Chapter 2.

Impacts of local energy solutions

Within ZEN we will study the impacts of local energy solutions, e.g. electricity produced by solar panels on building roofs. The impacts of 1 TWh / year extra solar power generation produced locally, could be somewhat than 1 TWh reduction in electricity consumption. The within-year profiles are not the same for consumption and solar power generation, and thus the corresponding reduction in power generation from other European sources, due to a changed balance in Norway, would be different for the two - hour by hour. As a reference, it could also be interesting to study the impact of extra wind-power generation. Furthermore, the impact of local solutions for supply of heating (or cooling) would have a different profile than a proportionally reduction in electricity consumption.

Impacts of local flexibility

Studies of local flexibility is also of high relevance within FME ZEN. With higher flexibility, the local energy system could respond to the needs of the total energy system, and/or reduce the needed transmission capacity within the grid between the local system and the surrounding system. This can be achieved by local energy system operations, and/or through the design of the local energy system infrastructure. For instance, electricity demand can respond more to electricity price variability, electricity demand profile can be shifted from peak load hours to off-peak hours, local storages / batteries can respond to prices and/or smooth out variability for local generation and consumption. From a modelling point of view, this can be implemented in EMPS through several methods, e.g. representing the flexibility by optimization variables or by processing of input parameters. The approach taken e.g. in scenario "X-16 Small and local" described in Box 3.1 can be an source of inspiration for this.

In a study of local flexibility, it may also be appropriate to utilize more detailed versions of EMPS (such as Sovn [16] or Samnett [17]) to be able to include more formal within-week optimization and/or more detailed representation of the electrical grid and corresponding congestion management. The detailed specification of how different types of local flexibility best can be represented in EMPS will however be developed within the corresponding study and not fully specified here. Fundamental models for price formation in markets for balancing services in a European market context are under development, and some tools could be available for this in some years [18].

For possible studies of the gains of having flexibility in energy solutions for specific areas, prices will typically be taken as an input to the analysis. It could be possible to include additional prices (e.g. intraday or for balancing services) to corresponding tools for local energy system operation (such as [19]). However, this will then be dealt with in task 5.1 of WP5, rather than in task 5.3 that is discussed there.

3.4 Planned scenarios and central sensitivity parameters for them

Main scenarios

The perspectives to be represented by the planned electricity market studies are described in Chapter 2. This is then the basis for specifying the set of main scenarios, cf. Table 3.1. As explained in Chapter 2, those main scenarios are intended to represent the main views in discussion on how reduced electricity consumption or other local energy solutions in Norway affect European CO_2 emissions.

Dealing with uncertainties

In general, it is not easy to forecast far into the future. Thus, it is far from trivial to calculate the impacts of a given change. There are several approaches to deal with uncertainties about the future. Often, a set of future *scenarios* developed. See e.g. Red, Green, Blue, Yellow and Ultra Green described in [4], and corresponding results in Figure 2.1. The scenarios are often different in several perspectives, and typically exhibit an internal consistency through a qualitative story-line for the future development. Among other things, scenarios often represent different outcomes of central uncertain factors, and there may be many differences in those factors between two scenarios. Another strategy to deal with uncertainty can be to change one single parameter at the time to study the impact of that particular uncertainty. This is often *sensitivity analysis*, at least if the study is carried out for a set of values for the uncertain parameter.

The main scenarios described in Table 3.1 represent the different perspectives described in Chapter 2. Thus, they are not set up to represent future uncertainty. However, in Table 3.1 we describe a set of uncertain factors that deemed important for the outcome of each scenario. We can then follow two different strategies with respect to the study of uncertainty, which is important for studies long into the future:

- A set of sub-scenario or versions may be defined for each main scenario, focusing specifically on one some of the important uncertainties for corresponding main scenario.
- A set of cross-cutting outcomes for uncertain factors may be specified (scenario for uncertainty), and then each main scenario are analysed for those outcomes.

The former approach provides the possibility to focus specifically on the most important uncertainties for each of the main scenarios. The latter approach will make it easier to give an overview of the set of scenarios that are analysed, and comparisons between different combinations in the set-up will be simpler. At this stage we leave it open (and up to discussion) if such cross-cutting future scenarios shall be specified, or if targeted sub-scenarios shall be defined for each main scenario.

Table 3.1 Suggested main scenarios

No	Name	Short description	Important uncertainty
1	Reference scenario	Future year dataset, e.g. one of the e-Highway scenarios for 2050.	[1)]
2	Marginal analysis	Reduced electricity consumption[2)] relative to reference. No change in capacities for generation or transmission, or permit prices.	Fuel- and permit-prices, installed capacities for various technologies
3	Long-term impacts[3)]	Reduced electricity consumption[2)] relative to reference. New optimal investments for generation, transmission, and retirements is calculated. No changes for permit prices.	Fuel- and permit-prices, support for RES-E generation (MWh), and/or firm capacity (MW), investment/maintenance costs, nuclear policy.
4	Emission permit market[7)]	Reduced electricity consumption[2)] relative to reference. Permit price is changed iteratively until emitted amount is the same as in reference scenario. [4)]	Number of permits
5	Adoptive policy-making	Reduced electricity consumption[2)] relative to reference. Permit price is set between reference value and price in emission permit market scenario.[4)] Cf. section 2.5.	Permit price
6	Cost-effective local energy solutions	The option to invest specifically in local energy system solutions is switched.[5)]	Investment costs local solutions, permit price, incentive (or regulation) for local solutions,
7	General equilibrium effects[6)]	Reduced electricity consumption[2)] relative to reference. Changes throughout the represented part of the economy is calculated, including but not limited to capacity investments, permit prices, and prices for various fossil fuels.	Number of permits, incentives or regulation for RES-E and/or local energy solutions

Notes to Table 3.1

[1)] Alternatives to the reference scenario (e.g. other e-Higway scenarios, cf. Box 3.1) could be relevant for the calculation of average emissions.

[2)] More generally, impact of local energy solutions are studied. Could be reduced consumption, extra renewable generation, or increased local flexibility. Cf. discussion in Chapter 3.3.

[3)] When studying the long-term effects through the impacts on optimal capacities, the initial capacities must be optimized too to get a consistent result. Then there are two options: Either the reference scenario has to be adapted to the optimization process for the investments in the EMPS model, or a new reference scenario is created specifically for the Long-term impact scenario. There are advantages and disadvantages for both approaches, including being able to compare results between the set of scenarios, and having a well worked-through well-known reference scenario taken from another major study.

[4)] Capacities for generation and transmission can either be calculated or fixed.

[5)] If the option to invest specifically in local solutions is explicitly represented in the reference scenario in the Long-term impacts scenario, then those options are omitted in the alternative scenario. However, if the option to invest specifically in local solutions is not explicitly represented in the Long-term impacts scenario, extra investment options are specified and included to represent such investments in the alternative scenario.

[6)] This scenario requires the calculation of an initial general equilibrium, before studying the impacts of reduced electricity consumption. The scenario is considered optional; the benefit of having it will be compared with the extra cost needed to provide it. A different simulation tool than EMPS has to be utilized. Possibly TIMES or MARKAL could be utilized for this.

[7)] Several approaches are possible here. One option is to model the whole emission permit market, e.g. emitted amount from all sources included in the system. However, for this study it is beneficial to focus on emission from the electricity market. Then emissions from all other sources can be considered constant or a predefined amount for the different years. An alternative could be to implement some simplified demand elasticity with respect to CO_2 permit prices for all other sources, if there are information about this in existing literature. Emissions from electricity generation should however be calculated, and the emission permit price should be the equilibrium price that balances the market.

3.5 Results – the outputs

For many of the planned scenarios mentioned in Table 3.1, the main motivation for including them is the variation in the environmental impacts of local energy solutions. Hence, the results in terms of CO_2 emitted from the power system generation will be the focus for all scenarios. Moreover, for all scenarios, power prices and total system costs are of interest. Other traditional EMPS model outputs such as power generation, transmission and energy balances are also likewise relevant.

For scenario no. 3, results for the invested amounts and installed capacities are important. For scenario no. 6, the share of investments carried out locally is particular interest, together with the socioeconomic impacts of utilizing local options and/or promoting them in regulation. An overview of the most important output from simulation are provided in Table 3.2.

Table 3.2 Important outputs: Impacts of measures taken locally

No	Output	Comment
1	CO_2 emissions	All scenarios
2	Permit prices	No. 4 and 7
3	Investments in generation and transmission, including the share for local energy solutions	Esp. no. 3 and 6.
4	Total system costs (or equivalently: total economic surplus)	Esp. no 6. Also for other scenario, but not always comparable results.
5	Power prices	All scenarios
6	Other EMPS output: Power generation, energy balances, and cross border trade	All scenarios
7	Other market impacts	Scenario no. 7

3.6 Other issues

Embodied emissions

Among other things, FME ZEB studied the how much embodied emissions there are in building materials for houses (see e.g. **[6**]). As we will include the energy system of areas in FME ZEN, it is of relevance to discuss the embodied emissions of energy systems as well. The EMPS model is a partial model for the electricity market, and thus it does not include a description of equipment manufacturing, construction markets, and corresponding CO_2 emissions from such activities. If there is a need for calculating embodied emissions in power generation equipment at the European scale, this can however be calculated separately on basis of included capacities in each scenario. Thus, we do not discuss this issue further in this report.

Heat

The impact of local solutions, including supply of heat, have been discussed in Chapter 3.3. This can be included in the EMPS model scenarios. By adapting local models for specific cases e.g. in eTransport, it is also possible to study more details about the competition and/or interaction between electricity used for heating, and other heating options e.g. district heating systems, local heating solutions, biomass such as wood-burning stoves, or rare examples of gas distribution systems in Norway.

Representation of local energy solutions in energy system models

For a power system model such as the EMPS model, no energy solutions can be more "local" than the geographically resolution of the model and dataset. Thus, the local solutions will in principle not be different from other energy solutions.[2] On the other hand, the specific characteristics of different energy solutions (including the local ones), can be specified through many different parameters such as:

- Installed capacities (e.g. in MW)
- Availability (e.g. within-year profile in per cent, identifying downtime / unavailability e.g. due to maintenance)
- For thermal power generation: Fuel type, the cost of the fuel, and efficiency in the conversion from the fuel to electricity, CO_2 factor (either per unit, or based on fuel and efficiency – with CCS as special case)
- For variable renewable generation (e.g. based on wind or sun): Within-year variability, e.g. hour by hour, for a set of climate years.
- For reservoir hydropower: Many additional parameters in EMPS model do describe the production systems in detail
- In investment analysis: Overnight investment costs, maintenance costs, life expectancy of investment etc to calculate annualized costs, possibly constraints in the invested amount e.g. to represent that the best locations will be taken first for renewable generation.
- Variation between different technologies and areas represented in the model is possible
- Profiles, especially for consumption, representing typically within-year profiles. Combined with temperature sensitivity within different weeks of the year.

Two important question are:

- To which extent is the energy system model able to represent local solutions, account taken to the objectives of energy system analysis?
- Are there sufficiently information and data available to represent local solutions appropriately?

Biomass, waste and similar

The emission coefficient for biomass is often set to zero because the released carbon during combustion have been absorbed from the atmosphere. The treatment of CO_2 emission from biomass combustion is, however, far from trivial. For instance, the harvesting of biomass may have impacts on the amount of carbon stored in the soil. Moreover, if the biomass is not used for energy purposes, most of it could be decomposed anyway eventually – with a corresponding release of carbon or other greenhouse gases to the atmosphere. For the study of the European power system, which is the focus in Task 5.3, biomass affects the analysis mostly when utilized as a fuel in power generation. As we have not planned to study specifically the CO_2 impacts of utilization of different types of biomass in power generation, one possible strategy for us can be to adapt approaches taken within UN or the EU, e.g. the rules that applies for the European emission permit market. A similar approach is relevant for utilization of waste. For now, we treat those issues open, with the plan of dealing with them in a pragmatic manner when carrying out energy system studies for Europe.

[2] A finer geographically resolution can be obtained by utilizing e.g. Samnett. However, the principle argument remains the same.

4 CONCLUSIONS

4.1 Summary

This document is a plan for the first European power market studies to be carried out within FME ZEN, in accordance with the project description and work plan for 2017. The goal has been to specify a set of scenarios that represent the different views that typically are taken regarding if and how environmental friendly local solutions can reduce European CO_2 emissions. The corresponding analyses will reveal how different perspectives affect simulation results, they will make it possible to compare different cases consistently since the same model and dataset have been utilized, and they will make it possible to explain the involved mechanisms, i.e. why results become different.

We have identified 5 main perspectives to be studied:

- Traditional approach: Marginal analysis
- ZEB approach: Average values
- Improving the traditional approach: Long term impacts
- Economists' view: Emission permit market
- A synthesis: Adoptive policy-making

In addition, we have described two other types of studies of high interest, but from different perspectives:

- Cost-effective local energy solutions
- General equilibrium effects

The described scenarios will be analysed mostly by the EMPS model. Needed inputs to the model are described, and an existing dataset of the EMPS model from the e-Highway project has been pointed out as a possible starting point for establishing a reference scenario. We have discussed, but not concluded finally on how to deal with uncertainty. Targeted sub-scenarios can be specified for each main scenario, or a set of cross-cutting scenarios can be developed.

We have discussed the factors that should studied, i.e. their impacts. In the FME ZEB, the energy system impact of a proportionally change in electricity consumption in Norway were studied. This can be a natural starting point also in FME ZEN. However, we have identified and discussed several alternative candidates, including the impacts of new renewable power generation locally.

We have also discussed which impacts that should be under study, i.e. which outputs we want to focus on. Apart from the obvious candidate CO_2-emissions, other relevant results include (but is not limited to): total economic surplus, power prices, permit prices, the share of local energy solutions in new investments, and energy balances.

Finally, we have discussed embodied emissions in power equipment, heat production, how local energy solutions can be represented in aggregated energy system models, and the treatment of CO_2 emissions from biomass. For several issues, the conclusion is left open for discussion, or they will be dealt with when carrying out the planned energy system studies.

4.2 Next steps

This report will possibly be the first finalized report within FME ZEN. Since no ZEN report format exist yet, we have made a SINTEF Energy report. However, it is the intention to lift it into a ZEN report format when this is ready.

This report is supporting documentation to the planned partner workshop 22. June 2017. The report will be finalized and sent to partners before the workshop. This workshop will influence on the planned energy system studies to be carried out within FME ZEN. However, the report itself is finalized before the workshop, and thus not modified afterwards. The formats for the communication of the revised plan has not be decided yet.

If possible within the budget for 2017, we will start the actual simulations of various scenarios that has been identified in this report. However, due to budget constraints, the work will possibly start in 2018.

4.3 Further power market studies

Whereas the first studies within FME ZEN focuses on the environmental *impacts* of local energy solutions, equally promising research perspectives are the study of the *role/share local solutions* will have in realizing the transition to a low carbon power system cost-efficiently, the *profitability of local solutions* under different ambitious levels for environmental policy, and the *impacts of different types of regulations* and incentives for promoting local energy solutions.

As a start, we will therefore prioritize to analyse the 5 different perspectives considering environmental impacts of local energy solutions. Thereafter, we will probably shift the focus more towards those other issues, including the two extra types of scenarios that have been mentioned (investing in local solutions, and general equilibrium effects). The line of study discussed for those scenarios will probably be developed and matured further before we actually carry such analysis. For the study of incentives and economic policy, we also foresee interaction with WP2 in FME ZEN.

It should be a goal to involve master students at NTNU in the work. They will typically use other methodologies and possibly develop their own models targeted towards some specific problem under study.

As a part of the work in this task, it will be beneficial to carry out a literature review. The scope and extent of this study will be defined in work plans for future years.

SINTEF

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A THE EMPS MODEL

A.1 Name, origin and usage

In the following we provide a brief description of the EMPS model. See [8] for a more detailed description. EMPS is the acronym for EFI's Multi-area Power-market Simulator. EFI was the acronym for Elektrisitetsforsyningens ForskningsInstitutt (English: Norwegian Electric Power Research Institute). SINTEF Energy Research was created as a merge between EFI and SINTEF Energy in 1998. The Norwegian name for the model is Samkjøringsmodellen.

The EMPS model has been developed over several decades at EFI and later at SINTEF Energy Research. Two main advantages of the model are the representation of uncertain weather, and the calculation of strategies for the utilization of hydropower reservoirs. The model is involved in the planning process for most of the hydropower generation in the Nordic area, and also used by TSOs and governmental agencies in monitoring and planning.

A.2 A fundamental model for system optimization

The EMPS model is an optimization model for a hydro-thermal power system. It is fundamental in the sense that that demand, supply and transmission is modelled with their corresponding characteristics. Formally, the model minimizes the expected system costs in the specified electricity system over a planning period. This is fully equivalent to maximizing total economic surplus when demand can be reduced at a cost specified by the demand function. Since a perfectly functioning market maximizes total economic surplus, there is a theoretical basis for using optimization model such as EMPS for forecasting in liberalized markets.

The numerical calculation in the EMPS model is divided into two separate parts. First, the model calculates a strategy for hydropower generation using stochastic dynamic programming (SDP). This is described in the next section. Secondly, the whole system is simulated week by week for each stochastic scenario using linear programming (LP). Figure A.1 illustrates an equilibrium for one area in one time-step.

During simulation, total system costs are minimized subject to all constraints of the problem, such as demand, transmission capacities, available generation capacity and the strategies for hydropower generation. The time-resolution during simulations be down to one hour, but water-values are calculated per week.

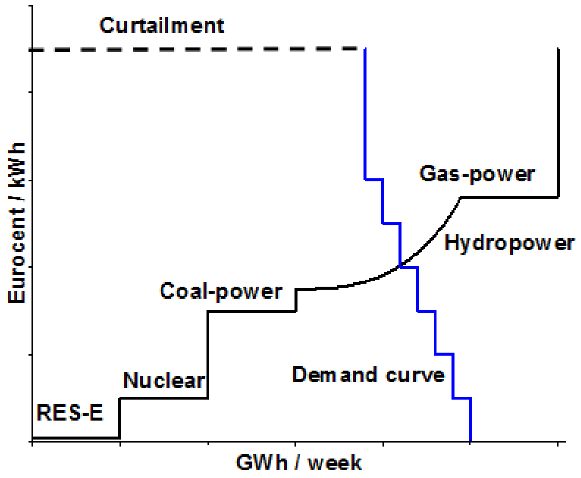

Figure A.1 Example of market equilibrium in a time-step

A.3 Hydropower

<u>Detailed representation</u>
A detailed representation of hydropower can be specified within the model, including specific reservoirs, generators, waterways, efficiencies, capacities, and hydrological inflow-series. Each model-user has their own dataset for the model, with different degrees of details and modelling approaches. Many users, such as the large producers, system operators, market consultants and SINTEF Energy Research have a detailed representation of the whole or parts of the Nordic system.

<u>Strategy calculation</u>
A strategy tells how to act under different circumstances. For hydropower, the strategy calculation problem is stochastic and dynamic because weather is uncertain whereas water can be stored in reservoirs. The stochastic variables in the model are inflow of water, outdoor temperatures, and varying renewable generation (wind-power, solar-power). However, climate variables are aggregated to one stochastic variable that goes into the strategy calculation. A variant of stochastic dynamic programming (SDP) called the water-value method is applied to calculate the strategy. See [20] for the methodologic background and history for water-value calculation.

Water-values are the marginal value of stored water. In EMPS they are calculated for a discrete set of reservoir levels, for each week in the planning period and for all areas where hydropower reservoirs are specified. The analysis starts in the final time-step (T), where the expected value of having additional water available is calculated by evaluating several outcomes for climate variables. This calculation is then done for a discrete set of reservoir levels, that combined give the water-value table for the final time-step. Now, the same calculation can be carried out for the previous time-step (T-1), taking the water-value for the final time-step (T) as the value of stored water at the end for this time-step (T-1). This backwards induction process continues until water-values have been calculated for all weeks in the planning period.

The end-value function, i.e. the value of water stored at the end of week T, is calibrated such that it would be the water-value for period T+1 if the final year had been repeated many times. An example of a water-value matrix for one area is shown in Figure A.2. It shows iso-curves for water-values (constant value curves) for different weeks and reservoir levels.

In principle, the water-value for a given reservoir is a function of all the mathematical states of the problem. This includes i.a. reservoir levels in each of the other reservoirs, realized values for each climatic variable (if there is auto-correlation) and the combination of thermal power generation units that is in operation (because of start-up costs). The size of this optimization problem is so large that it is not possible to solve at acceptable computational times using SDP. This challenge is called the curse of dimensionality. The optimization problem for the strategy calculation must therefore be simplified, and in the EMPS model this is handled as follows:

- All reservoirs within an area is aggregated to one equivalent reservoir and station
- Water-values are calculated for each hydropower-area in isolation. A residual demand (demand adjusted for supply from other technologies) is allocated to each area.
- Other state-variables than reservoir levels (e.g. possible auto-correlation in climate variables and the set of thermal power generation that is in operation) is not accounted for when calculating water-values.

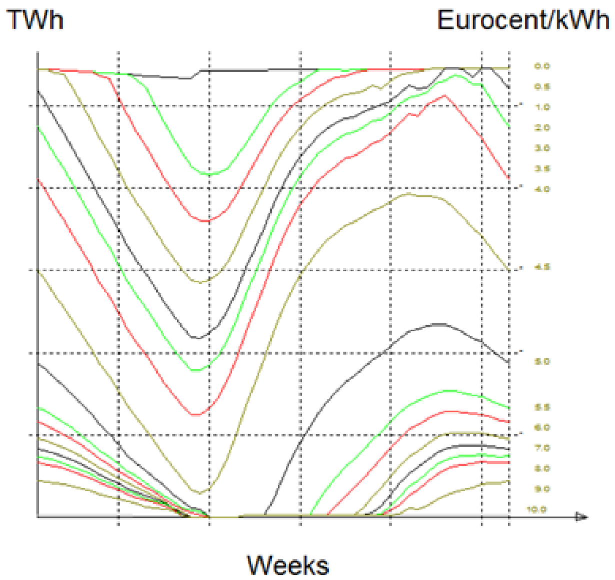

Figure A.2 Example of water-value matrix

<u>Simulation</u>

When water-values have been calculated, they are treated as marginal costs for hydropower. Now the model carry out a week-by-week cost-minimization for the whole simulated power system (e.g. parts of Europe) for instance for one year. The within-week time-resolution can be 1 hour or longer. The weekly simulation is carried out for each stochastic scenario, which are actual realization for climate variables (so-called climate years) e.g. for the period 1948 – 2015. Typically, a simplified area-to-area transmission grid representation is applied. During simulation, the location for demand and all supply are set in accordance with the inputs to the model.

For a given week, there are several simulation/optimization sequences. First, the aggregated "area-optimization" is carried out. In this optimization, the aggregated equivalent hydropower description is applied and total system costs are minimized. The area-optimization can be solved using LP, but sometimes more efficient techniques that utilize the structure of the problem are applied.

Secondly, the solution for hydropower generation for each area from the area-optimization is allocated to the modelled stations for respective areas through a rule-based logic that basically minimizes the danger of reservoir spillage. This part of the simulation is called the "draw-down model". If the area-production is unfeasible because of constraints in the detailed model, the area-optimization for this week is recalculated. The detailed model also calculates an update of efficiencies, which are parametric inputs to the area-optimization. For each week, the area-optimization and draw-down model is solved repeatedly in an iterative procedure until convergence. It is also possible to apply more formal optimization instead of the rule-based draw-down model [16].

Calibration

Because of the mentioned simplifications in water-value calculation, the model must be calibrated by the user on basis of simulation results. There are several calibration factors per area that can be utilized in this process. Calibration factors basically adjust the demand (annual level and within-year profile) and price-flexibility (for demand and other supply-types) that goes into the water-value calculation for each area. The traditional criteria for calibration is to avoid too much spillage in wet years, good within-year utilization of reservoirs, avoid curtailment if possible, and avoid too much systematic within-year price-variation. Some users calibrate the model to imitate statistics for reservoir level handling or other variables. The model can also do an automatic search that improves the calibration step by step in an iterative process, e.g. using total economic surplus as criteria.

A.4 Other model components

Thermal power generation

Thermal power generation includes nuclear power, gas-power, coal-power, oil-power and bio-power. Individual power plants can be modelled. The modelled units are described by marginal costs (or efficiencies combined with fuel- and CO_2 prices), capacity, within-year availability and start-up costs (optional). Without the start-up costs, a unit is in operation if marginal costs is less than the price. If start-up costs are specified, a sequential within-week optimization is carried out. This is not a full unit commitment MIP implementation, but a linear approach that allows aggregation of units. The end-state for started capacity in one week is an initial condition for the next-week optimization.

Wind-power and solar-power

For each simulated climate year and area there are series representing wind- and solar-power variability. Whereas the variability typically is based on data for the corresponding climate years, the actual generation is scaled with the installed capacity for the simulated year (could be e.g. the current year or a given future year).

Consumption

There is large flexibility for the specification of demand. For ordinary demand, annual consumption as well as within-year and within-week profiles are typically specified. Several demand types/units can be specified for each area. The demand can respond instantaneous or gradually to prices, or be independent of prices. It is possible to specify a temperature-dependency for demand (GWh/week per degree Celsius), and in this case weekly temperatures are stochastic variables in the model. For some industrial demand and dual-fuelled boilers, demand is often specified as weekly quantity and a price, which may be different for different weeks.

Transmission
In the standard version of the EMPS model, the connections between different areas are treated as controllable transport channels. This implies that the maximum transmission capacity is utilized between two connected areas unless the price-difference is less than the value of transmission losses. The capacity can be different for different weeks, but are typically the same for all simulated climate years. Losses can be calculated as a proportion of the transmitted amount or as a quadratic function. It is also possible to attach a specific transmission tariff that comes in addition to the implicit transmission cost through losses. It is possible to carry out detailed power flow, including congestion management based either on system-optimality or a rule-based procedure that reduces the capacities of transmission lines used in the market-clearing process, see e.g. [17].

Curtailment
In case inflexible demand exceeds available generation capacity plus import capacity, the market equilibrium is obtained at high system-costs through curtailment, i.e. enforced reduction in demand. In Figure A.1 this is illustrated by the dotted part of the demand curve.

A.5 Outputs and simulation modes

Outputs
All model-variables can be extracted for each time-step. In practice, the amount of information that is available is so large that one has to prioritize and/or summarize. Several result-programs have been developed to make this easier. Simulation results of interest can for instance be average values or probability distributions for prices, transmission, economic surplus, reservoir handling, spillage or curtailment.

Simulation modes
For the operation of the system, there are two alternative simulation modes: series and parallel. In a series-simulation, reservoir-levels at the end of week 52 in scenario 1948 will be equal to the reservoir level at the start of week 1 in scenario 1949. This mode is typically utilized when analysing a given future year since this also gives a variation with respect to the reservoir level in the beginning of the year, which is unknown for a given future year. In a parallel simulation, the reservoir levels at a specified value for week 1 for scenario. This model is typically utilized when forecasting, e.g. next year, or when analysing a given historical year. In such cases reservoir-levels at the start of the planning period are in principle known for the year we want to study, and thus the information should be included in the model.

In addition to the simulation modes for the operation, the EMPS model can be can be run in investment mode. That mode calculate investment- and retirement decisions for capacities. In the model solution, all profitable investments/retirements for generation and transmission capacities are carried out for a given future year, whereas none of the included investments/retirements is unprofitable [9].

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