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Significance of Smart Grid technologies in electricity system: scenarios of wind power and heat storages

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Summary

The goal of this report is to *study the effects and significance of Smart Grid (SG) technologies in (future) energy systems.* The topics are approached by computational model based scenario analysis, for which there are a variety of energy system models available.

The suitability of available energy system models was explored and preliminary tested with respect to the goals of this study. As a result, a recent modification of Wilmar Planning Tool, describing Nordic energy system, was applied. This implicates that traceability and micro-level demonstrability of the scenarios are of high priority.

The motivation for the development of Smart Grids is to a great extent to do with integration of renewable energy resources in electricity systems. In controversial to conventional generation, renewable electricity is often undispatchable and varies stochastically over time. This is especially relevant with wind and solar power. Thus, matching up the consumption and generation of electricity in the future calls for novel solutions and technologies.

Of large variety of technologies discussed in SG context, scenarios here are defined to explore the effects of the (i) increasing amount of wind power and (ii) the role of heat storages. By modifying the WILMAR database and conducting model runs, scenarios of hourly production volumes of Nordic energy system in such SG context over a simulated year, are obtained as results. The amount of wind power is scaled to represent the targeted level of the EU by 2020, whereas the size of hear storage between 0-10560 MWh is located in the heat area describing urban Finland.

Differences in Combined Heat and Power Plant (CHP) operation modes of the urban area of Finland were observed between SGEM characterized scenarios. Heat storage causes on-off behaviour on electricity production of CHP plants, different to smoother shaped production curve when storage is no available. The on-off behaviour is seen especially in category steam turbine back pressure plants. Annual production values in Nordic level do not show differences.

The results of the scenario runs must be seen as of demonstrative nature. As a main result of the study, preliminary experiments of suitable modelling tools for system effects of SGEM technologies were conducted.

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Preface

The study is part of the Smart Grid and Energy Market (SGEM) research programme, which in turn is part of the Finnish research cluster Cleen Oy. The SGEM project is financed by Finnish Funding Agency for Technology and Innovation (Tekes), industrial partners, universities, and research institutes.

The report describes the results from task 1.1.2 “Electricity from society point of view” as a part of SGEM 1 funding period work package “Significance of electricity and Smart Grids” (SGEM 1FP WP1.1). The first funding period started in 2009 and ended 28.2.2011.

According to the current energy and climate policies e.g. of the European Union, it seems likely that renewable energy, often distributed and non-dispatchable, is more and more integrated in electricity systems in the future. Due to growing need of matching up the consumption of electricity with varying production, energy storages, electric vehicles and demand side integration are under growing interest of potential future solutions, the SGEM research programme and this study.

The idea of the subtask 1.1.2 was specified in studying the role of SGEM related technologies in the future Finnish and Nordic electricity systems. A model-based approach is chosen, where the characteristics and outcomes of future electricity systems are studied by scenario analysis.

The authors wish to thank the funding organizations and the steering group of SGEM programme for making this work possible to carry out. We also like to thank Mr. Erkka Rinne and Mr. Juha Kiviluoma especially for their valuable guidance in adoption and use of the Wilmar Planning Tool model applied in the study.

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Authors

Contents

1 Introduction

According to the current energy and climate policy targets e.g. of the European Union, it seems likely that renewable energy is more and more integrated in electricity systems in the foreseeable future during the next few decades (see e.g. Ruska & Kiviluoma 2011).

Smart Grid (SG) is a term used for a 21st century electricity network (see e.g. EC (2010) for description of the Smart Grid concept). Briefly, the aim of SGs is to utilize modern information technology to enable the evolution of grids towards more efficiency.

SGs are currently under intensive research and development. The motivation for the development of Smart Grids is to a great extent to do with integration of renewable energy resources in electricity systems. That is, in controversial to conventional generation, renewable electricity is often undispatchable and varies stochastically over time. This is especially relevant with wind and solar power. Thus, matching up the consumption and generation of electricity in the future calls for novel solutions and technologies.

The change brought by the new environment of SG concerns the use of electricity, elasticity of demand, mobile loads, large penetration of DG and energy storages etc. Due to growing need of matching up the consumption of electricity with varying production, energy storages, electric vehicles and demand side integration are under growing interest as potential future solutions and this study as a part of future Smart Grids. Heat storages are among the technologically most mature solutions. As a demonstrative example, their effects and related phenomena, when integrated in the future electricity systems characterized by growing share of varying electricity production, are focused in this study.

The idea of the subtask 1.1.2 of the Smart Grid and Energy Market (SGEM) research programme was specified in studying the role of SG related technologies in the future Nordic and Finnish electricity systems. A quantitative model-based approach is chosen, where the characteristics and outcomes of future electricity systems were studied by scenario calculations from energy system models. The results of the experiments are reported in this paper.

2 Goal

As a part of SGEM WP 1.1, *“Significance of electricity and Smart Grids”*, in the task 1.1.2, *“Electricity from society point of view”*, the following topics were initially specified to be of interest:

- What is the contribution of Smart Grids on national level?
- What would a SG-based energy system look like?
- How does it differ from conventional system?
- What is the effect of SG on policy options?

Thus, the effects on economics and energy production, and phenomenon brought by SG systems and related technologies were aimed to be discovered under these areas. More broadly, the goal of the task is expressed as to *study the effects and significance of SG technologies in (future) energy systems*. Kiviluoma & Meibom (2010a, 2010b) provide examples of related research under this framework.

The topics are approached by computational model based scenario analysis, for which there are an abundance of models available. With method and research question identified, the task can be divided in the following sub-tasks:

- Choose a suitable model for this study on a basis of experiments of available models in SG environment (Ch. 3)
- Define the characteristics and parameters in scenarios studied (Ch. 4)
- Implement the changes in the chosen modelling system
- Run the model
- Analyze the results (Ch. 5)

3 Methods

A method used in the study is *scenario analysis*. Here, the sometimes ambiguously used term means that extensive, computational energy system models available at VTT Technical Research Centre of Finland are utilised to give indications to topics under interest.

Scenarios are to explore different, yet still plausible possible future development pathways or operational modes for the system in the future. Please note that scenarios presented are not constructed to be forecasts. The realising future is largely affected by policies, economic development and actions of market participants in uncertain real-world environment that are not considered here.

Given the parameters and the computational model of the energy system (power plant stock, electricity and heat demand, and costs of fuels…), optimal use or development trajectories of electricity systems, as well as information on related economic or environmental variables can be obtained as a result. As input parameters of the models are varied, the effects of different technological set-ups can be simulated and studied, and, insights to research topics specified in Chapter 2 can be obtained.

With a rich variety of continuously evolving energy system models available at VTT, the appropriateness of models to be utilized in Smart Grid environment and suitability in this study was shallowly scanned. There are pros and cons in each model system, and universal solution for every kind of problem hardly exists.

In the end, the candidates for this study turned out to be TIMES-VEDA and Wilmar Planning Tool based models. Wilmar Planning Tool based model was eventually chosen to be applied in this study, and the scenario runs presented in Chapter 5 are conducted by it. This Chapter discusses briefly with scenarios methods, generally on properties of energy system models, as well as differences and pros and cons of models considered.

3.1 Generally on scenario analysis method

In this report, term scenarios refer to energy system model calculations of the alternative development paths or operation modes. Scenario results in this report are obtained as a result of an optimization process. Scenario represents the optimal way of conducting modelled real-world energy system according to chosen criteria (e.g. least cost of producing energy with available capacity), while satisfying a set of constraints (e.g. supply must at least equal demand at every point in time).

Assumptions behind alternative scenarios presented differ with respect to, e.g. technological development or technology available, production conditions such as outdoor temperature, precipitation, windiness etc. Different assumptions may lead to differences in scenario results. The differences can occur in energy demand, least-cost production methods or greenhouse gas emissions in the results of the model calculations.

However, it has to be stated that “--- scenarios should not be considered as representing forecasts or predictions of reality, but rather as optimal trajectories indicating the most cost-efficient decisions of producers and consumers while satisfying all the demand projections and other constraints.” (VTT 2009)

According to VTT (2009), it is common practice to classify long-term scenarios into three important types: so-called reference or baseline scenarios, exploratory scenarios and policy scenarios.

- **Baseline scenarios** largely assume the continuation of historical trends and policies into the future and that the structure of the system responds in predetermined forms.
- **Exploratory scenarios** are designed to explore several different, yet still plausible future development pathways for the system. Their main purpose is usually to identify the most robust decisions from the standpoint of the main stakeholders: e.g. policy-makers, energy producers or technology developers. Exploratory scenarios can provide a good appreciation of the uncertainties that lie ahead in the system development.
- **Policy scenarios** are designed to analyse the impact of introducing some new policies, or a set of desirable characteristics that the future world should possess according to the agent elaborating the scenario.

3.2 Energy system modelling, model categories and their characteristics

Energy system models are applied to explore operation of energy systems. Generally, mathematical and statistical methods are utilized in the models. The dimensions of energy system under interest can vary within large limits - from e.g. balancing heat and electricity supply and demand of a single house to that on a global level. Models can be utilized in many ways - phenomena of the system can be learned and the effects of alternative decisions can be analysed. Strategies to strengthen or diminish the observed effects can be analysed. In modern applications, the models and calculation are practically implemented computer-aided.

The models can be categorized according to several criteria (Rinne 2011)

- **Bottom-up vs. top-down models.**
  - Bottom-up models usually include more sophisticated technology-based description of the system
  - Top-down models describe the characteristics of whole economic system, including the relationships between labour, capital and natural resources. Usually, description of technological processes is not as advanced as in bottom-up models.
- **Long-term models vs. short-term models.**
  - Long-term models explore the development of an energy system over a time period of years of decades. They give indications e.g. of subsidies or regulations on investments made on the system.
  - Short-term models deal with fixed generation capacity and they give indications of optimal scheduling of power plants, typically on a time scale of day or hours ahead.

Top-down models take a *macro view* on subjects since they generally deal to a greater extent with aggregated units and national, annual variables. In contrast, bottom-up models take *micro view* takes a look to variables under interest e.g. at a level production units.

3.3 Discussion of models considered for the study

3.3.1 TIMES-VEDA modelling system

TIMES-VEDA modelling system for technical-economic analysis of energy system scenarios (Loulou et al. 2005) was a first considered modelling tool to study the scenarios on the effects of SGEM related technologies in task 1.1.2. Thus, the TIMES-VEDA modelling system (i.e. the data-bases, interface control program and model generator) was installed and preliminary tests of feasibility of the TIMES-VEDA model used in Forsström et al. (2010) to address the goals of this study were conducted.

3.3.1.1 General characteristics

The TIMES-VEDA based model considered is a partial equilibrium bottom-up energy system model. Detailed description of different energy forms, resources, conversion and processing technologies and end-uses, while taking projections for the rest of the economic system as external projections, are included. Commodity prices and consumptions are calculated through price elasticities of demand throughout the energy chain, providing a market equilibrium solution for the energy sector. The model is thus suitable for assessing the effect of the energy system alone on, for example greenhouse gas emissions, or industry development, holding other factors constant.

Given the input data on technological development, resource availability and different end-use demand projections, the model calculates the resulting scenario by **minimising the present value of the total global energy system costs, including plant investment**, commodity and process activity costs, but also the cost of lost demand due to price hikes of commodities. (VTT 2009)

In the TIMES version considered (Forsström et al. 2010), Finnish energy system is in detail described. The export and import of electricity is obtained through economic optimisation by market prices of electricity, obtained from MH model (Kekkonen & Pursiheimo 2005). The transmission capability of Nordic electricity grid is assumed sufficient in this set-up.

3.3.1.2 Description of time dimension in TIMES

The time horizon of a TIMES model is represented through model years. To control the model size, the model years can be combined and represented in a simplified way, by periods. The second time dimension of the TIMES model is sub-annual. This is especially relevant for SGEM considerations. For modelling electric load curves, space heating demands and traffic in TIMES model, the year can be split according to seasonal, weekday / weekends, and hours of the day characteristics, composed into *timeslices*. (Gargiulo 2009)

“Timeslices of TIMES-VEDA models may be organised into four hierarchy levels only: “ANNUAL”, “SEASON”, “WEEKLY” and “DAYNITE” defined by the internal set timeslice level. The level ANNUAL consists of only one member, the predefined timeslice “ANNUAL”, while the other levels may include an arbitrary number of divisions.” (Gargiulo 2009)

Construction of timeslices in the TIMES version considered (Forsström et al. 2010) follows the set-up of 4 Seasons (S=Summer, F=Fall, W=Winter and R=Spring) and three Daynite (D = Day, N=Night and P=Peak) time slices. Constructing the time slice tree this way, 12 time slices, according to which the load curves and sub-annual variations are modelled, are established.

3.3.2 Wilmar Planning Tool

WILMAR (*Wind Power Integration in Liberalised Electricity Markets*) research project was conducted in 2002-2005. The focus of the project was to find out economical and technical implications of fast introduction of large amounts of intermittent renewable power production, such as wind power, in power systems. As one result of the project, a modelling tool *Wilmar Planning Tool* was introduced. The development work of the model has been continuing after the project by its parties, e.g. at VTT Technical Research Centre of Finland. (Rinne 2011)

JMM (Joint Market Model) is one of the several components and databases of Wilmar Planning Tool. It is an analytic bottom-up partial equilibrium model, reaching to economic equilibrium (matching supply and demand) in electricity markets. JMM is a short-term scheduling model, whose result is obtained by optimizing the economic dispatch and unit commitment of heat and power plants though a time horizon of following day, fulfilling the electricity and heat demand and reserve requirements. The model is usually run for on a timeframe of one year, and optimum is obtained on hourly resolution.

Particularly, performance of dedicated integration technologies like electricity storage can be evaluated by the model (Nørgård 2004). The JMM also includes stochastic mode and attached components, but they are not used in scenario runs of this study.

A recent modification of the Wilmar Planning Tool model (Rinne 2011) was installed and used in this study. This version uses JMM with MH model (*MH-malli, Markkinahintamalli*) developed at VTT to compute the water values used in optimization. These values are used by JMM in determination of economic dispatch. Wilmar Planning Tool covers detailed descriptions of power and heat system in Nordic countries whose electricity markets (Finland, Denmark, Sweden, and Norway) are integrated. Also heat supply and demand are modelled. Minor changes to its structure and parameters were implemented to tackle the goals of this study.

3.4 Discussion of differences and suitability of models considered

As the TIMES-VEDA system produces, more or less, a macro view (although it is a bottom-up environment) and SGEM related technologies typically operate in a micro environment, a problem arises as to how to combine these two. Therefore, initial plans to implement the models of this study with TIMES-VEDA, were taken into further consideration.

In preliminary investigations of appropriateness of TIMES energy system model version considered for this study (used e.g. in Forsström et al. 2010), it was found out that the version deals with sub-annual short-term power system balancing and unit dispatching only roughly. Thus, it was concluded to look for models where sub-annual internal variations are more thoroughly taken into account. These phenomena are especially relevant for SGEM considerations.

Consequently, Wilmar Planning Tool based model was found to fufil such requirements and considered more feasible for this project, taking the time and resources available for the study into account. The resource limitations did not allow major changes in the structure of TIMES model. The WILMAR based model is able to simulate the Nordic electricity market by hourly resolution, capturing many of the characteristics of SGEM environment. The time frame for Wilmar Planning Tool optimization is one year. Thus, it is assumed that the electricity and heat system equipment are constant over the year.

It can be stated that TIMES-VEDA based model might have given a broader picture of whole long-term energy system development. This is due to the fact that in addition to energy production transportation sector, industrial and building sectors are modelled with technological bottom-up descriptions, as well investment options and interplay between sectors is included.

The decision to use of Wilmar Planning Tool in this study implicated that traceability and micro-level demonstrability of the scenarios are of high priority, whereas system-wide long-term evolution and macro-level effects may have been better tackled with by TIMES-VEDA based scenarios.

4 Description

4.1 Technologies under interest

A wide variety of end-use and generation as well as energy storage options are discussed in a context of future Smart Grid environment. On the one hand, technologies are discussed as evolving options for the future low-carbon energy systems and, on the other hand, as solutions to deal with future electricity systems characterized by increasing shares of intermittent and distributed generation.

Key technologies initially considered in SGEM environment include at least:

- Plug-in-hybrids and electric vehicles
- Distributed generation technologies
- Wind, solar, or biomass based generation technologies
- Battery and other storage technologies
- Heating solutions

Heat storages are technologically mature solutions and have been used in Finland for decades (Alanen et al. 2003; Kara et al. 2004). There are several technological concepts under a category of heat storages. In this study, large-scale centralized storages are under further interest. This type of storages is installed as a component of Combined Heat and Power (CHP) plants, and water is used as a medium.

Wind power capacity is estimated to be the largest renewable electricity technology by 2020 in the EU. This assessment is based on the EU Member States National Renewable Energy Action Plans (NREAP), required to be published by the end of July 2010. The NREAPs provide detailed roadmaps on how the Member States expect to reach their legally binding targets for 2020. Wind power capacity is projected to more than double to 213 GW in 2020. (Ruska & Similä 2011)

4.2 Characteristics and assumptions of scenarios studied

Heat storages and wind power seem to be technologically among most mature of large variety of SGEM technologies. Furthermore, wind power is assessed to be the most rapidly increasing renewable electricity technology in the EU by 2020. With these technologies, experiments are also relatively easily implementable in the model and traceability can be maintained when only few parameters are tuned.

These facts justify wind power and heat storages are chosen as “building blocks” for scenarios where operation of energy systems in SGEM environment is studied by Wilmar Planning Tool (Rinne 2011). That is, by varying technological parameters of heat storages and increasing wind power in the model their impacts are aimed to be discovered. In this section, the assumptions and parameters are reviewed more detailed, whereas the results of model calculations are analysed in Chapter 5.

The years and power plant stocks for years 2000, 2001 and 2002 are described in WILMAR database. Thus, there are differences with currently (2011) installed power plant base. However, we study the feasibility to test the effects SG characterized electricity system by this model, and the results must be seen only as of demonstrative nature.

The names and general characteristics of scenarios are presented in Table 1.

Table 1. Differences in the assumptions of the scenarios studied

Name of the scenario	**Share of wind power in Nordic countries**	**Heat storages**	**Other parameters**
Reference	Corresponding 2001 production	As installed in 2001 in WILMAR database; none in Finland	WILMAR database default values (2001)
No storage	Corresponding the 2020 target levels	As installed in 2001 in WILMAR database; none in Finland	WILMAR database default values
Single storage	Corresponding the 2020 target levels	Additional 5 280 MWh installed in Finland (Urban area)	WILMAR database default values
Double storage	Corresponding the 2020 target levels	Additional 10 560 MWh installed in Finland (Urban area)	WILMAR database default values

4.2.1.1 Determination and modelling of wind power production in the scenarios

The 2020 targets are used to calculate feasible quantities for wind power increase of the Nordic countries covered in the model. Targets from NREAPs (Beurskens & Hekkenberg 2011) are used for Finland, Sweden and Denmark. For Norway, a figure representing realistic potential for 2020 is from Tande (2006). These figures are presented in Table 2.

Table 2. Wind power capacity in Nordic countries (MW) and targets for 2020.

	2001 capacity in WILMAR database (MW)	Target for 2020	Scaling factor
Finland	39	2500	64.1
Sweden	328	4547	13.9
Norway	17	7000	411.8
Denmark	2524	3960	1.6

We use a simple method of scaling the realised hourly wind power production of 2001 to represent the increased production of SGEM environment in the model. That is, e.g. for Finland, the hourly production in the database is scaled by a factor (2500/39=64.1) for each hour of the year etc. For Finland, this means 5.4 TWh, of annual wind power production assumed in the model (the realised production for 2001 was 0.07 TWh). As a comparison, historical data for electricity demand for Finland in 2001 in the model is 79.1 TWh. It can be seen that hourly values in January of the modelled year in Finland vary between from virtually zero to some 65 % of the theoretical maximum value.

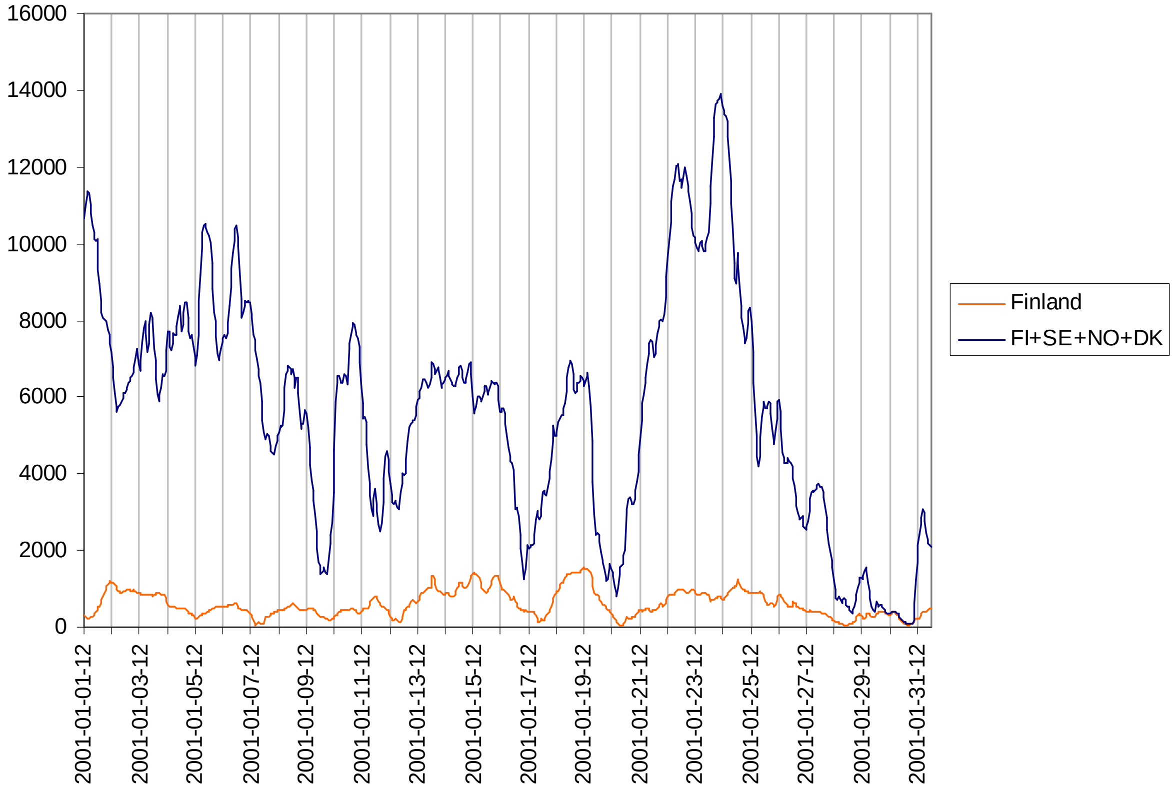

Fig 1. Hourly wind power in January in Finland and in Nordic countries assumed in the scenarios other than reference scenario. Variation is seen in different timescales.

Fig 1 is included to demonstrate variability in wind power production in Finland as well as in the Nordic electricity market area (Finland, Sweden, Norway, Denmark) in the scenarios (other than the Reference scenario).

4.2.1.2 Determination and modelling of heat storages in the scenarios

The Wilmar JMM model includes a sub-national regional structure to ensure an adequate modelling of energy supply. That is, each country is divided in *regions* to model internal congestion in power grid. Regions are further divided in *areas*, according to which the heat supply is provided. In Finland, there are three areas in the model: urban, rural and industry, representing the heat load of industries.

The heat storage varied in scenarios is located in urban area of Finland. It is modelled on a basis of Heat Storage modelled in a database *(UnitGroup: FI_R_Urban_HSTO, UnitGroupID: 3059)*. Technical parameters valid for the scenarios of this unit group are

- MaxPower: 660 MW
- Sto_MaxCharging: 660 MW
- Sto_MaxContent: default 5 280 MWh, *varied between scenarios*
- LoadLoss: 0.999

The parameter LoadLoss implicates the effiency of storage when loading (Energy stored/Energy input) (Kiviluoma & Meibom 2006). From the database values, we see that in *FI_R_Urban* area, the difference between the maximum heat load at nighttimes and minimum heat load in daytimes is in the first week of January some 200 MW. From the parameters it can be calculated that with default values, the storage is charged to a maximum value as well as discharged in 5280/660=8 hours. Furthermore, if the storage is e.g. loaded full during daytimes, it is capable of delivering the additional night-time load for 5280/200=26 hours. Thus, storage of this type can be used to e.g. match the variability in short term (charging-discharging cycles of days and intra-day).

5 Results

The version of Wilmar Planning Tool modelling system (Rinne 2011) was installed to explore the scenarios, whose assumptions are defined in Chapter 4. In this Chapter, the results of optimizations are presented and analysed.

5.1 Observations in scenarios

5.1.1 Impacts in Finland

A visual inspection of electricity production structure in Finland revealed differences between scenarios in electricity production of *FI_R_Urban* area (see Fig 2 for an example of the model run results). Thus, it seems that the operation modes CHP plants are affected in the modelled scenarios with increased wind share and heat storage.

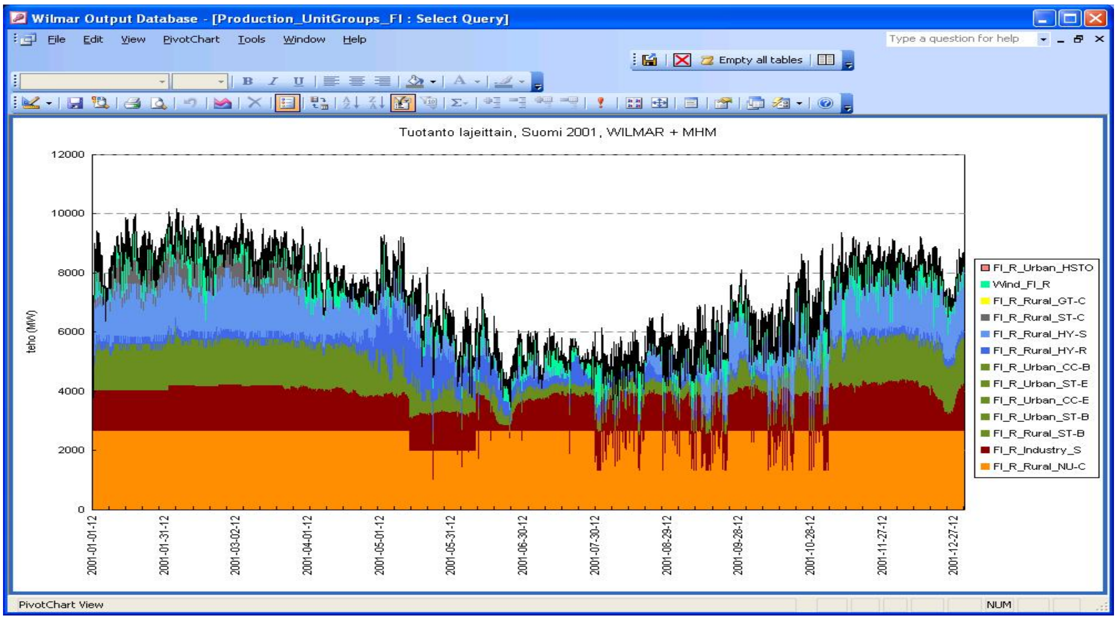

Fig 2. An example of the scenario results: the annual electricity production of Finland by technologies by hourly resolution, "Single storage" scenario.

Heat storage is also used charged and discharged in the scenarios where it is included. Fig 3 represents January of the studied *Double storage* scenario. In the scenario, there are roughly seven charge/discharge cycles in January, which gives an approximate length of four days per charge/discharge cycle.

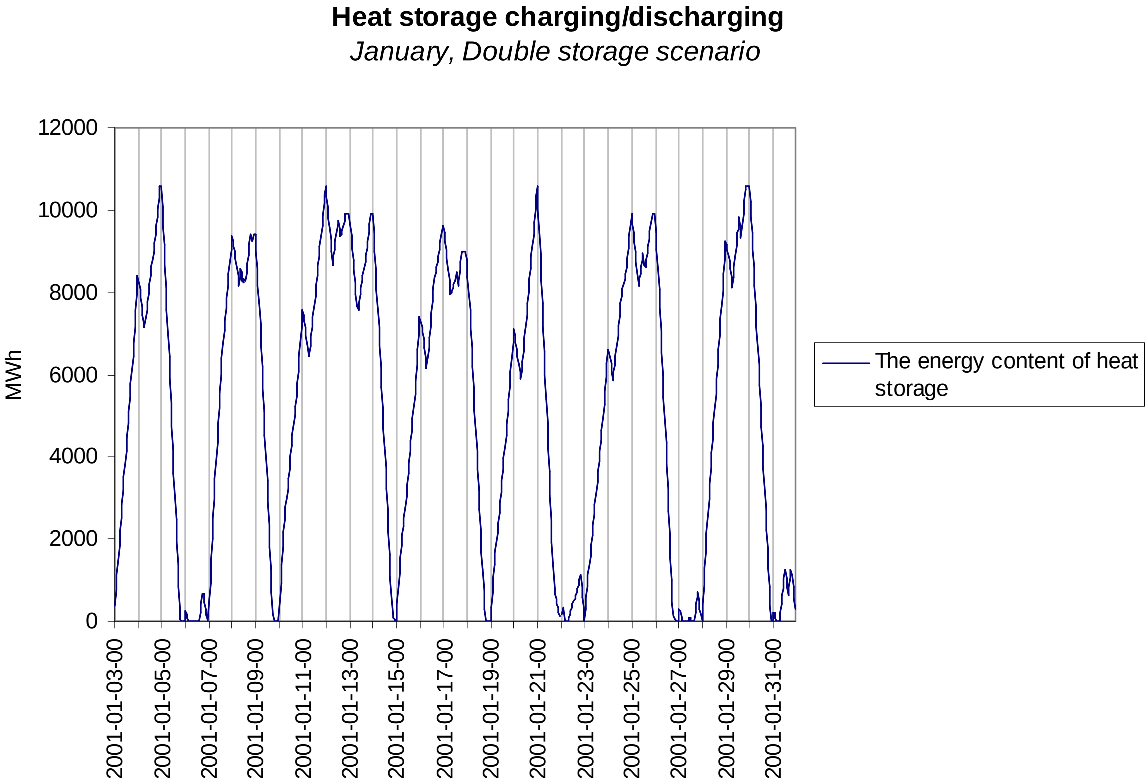

Fig 3. The energy content of heat storage, Double storage scenario, January.

January of the studied year was chosen as a test period to further explore the scenarios. This is of particular interest since both the electricity and heat demand are high. Fig 4 shows electricity production by CHP plants of all technologies during the first week of January in the *FI_R_Urban* area.

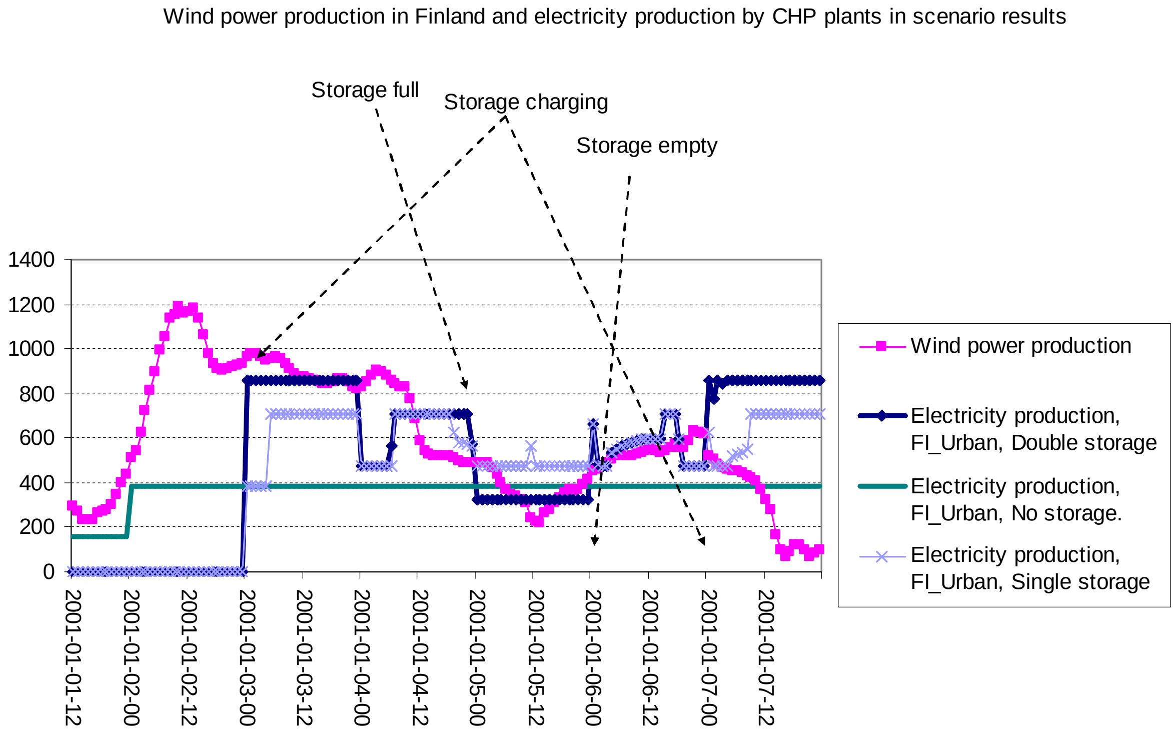

Fig 4. Electricity production of CHP in the scenarios, first week of January, FI_R_Urban area. Scaled wind power production curve in Finland and the moments for starting charging/discharging are plotted as potential explanatory variables.

There are following CHP technology groups and units are located in the *FI_R_Urban* area of the model[1].

- ST-B - Steam turbine, backpressure; Hanasaari B, Salmisaari
- ST-E - Steam turbine, extraction; Hanasaari A
- CC-B - Combined cycle, backpressure; Vuosaari A
- CC-E - Combined cycle, extraction; Vuosaari B

Fig 5 and Fig 6 illustrate the difference of electricity production of ST-B category over the whole simulated year and January in *No storage* and *Double storage* scenarios. We can clearly observe increased on-off type of operation in this category if heat storage is available. If it is not available, the electricity production curve shows similar shape as heat demand. The maximum electricity production for Hanasaari B plant is 226 MW, and for Salmisaari, 160 MW.

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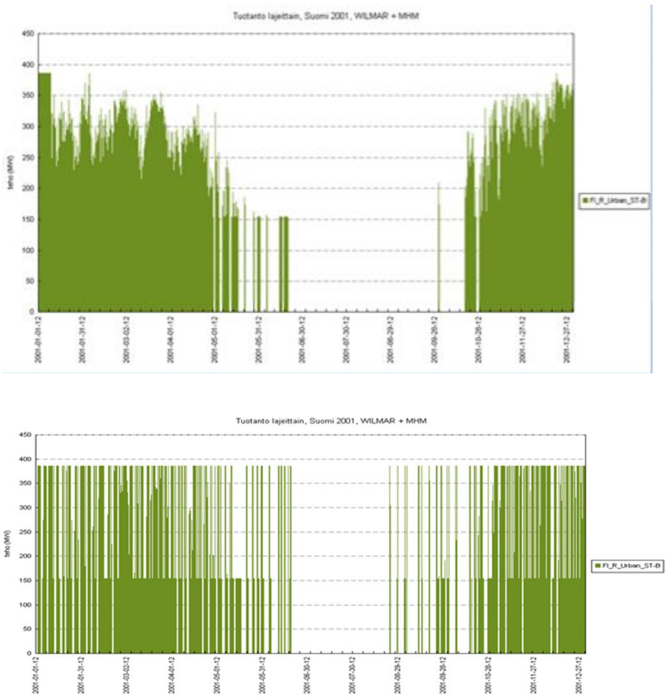
[1] The facilities are named in Swedish in the database



No storage

Double storage

Fig 5. Annual electricity production by hours, ST-B category, FI_R_Urban area. The upper graph presents the production of No storage scenario and the lower graph that of Double storage scenario.

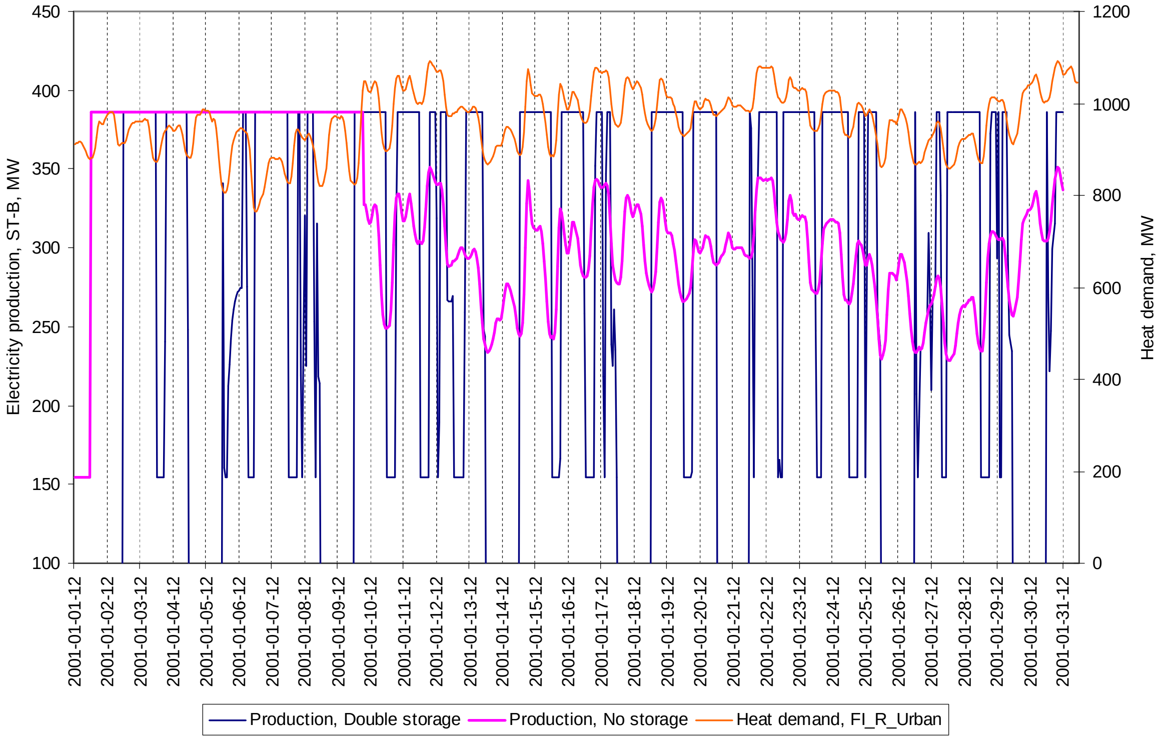


Fig 6. Electricity production by hours in scenarios, ST-B category, FI_R_Urban area (left scale) and heat demand (right scale), January. When heat storage is not available, the electricity production seems to be smoother and to follow the heat demand. If storage is available, the power production is more variable.

Overall, on a basis of the results of the model runs, the following observations are made (see Fig 4 and Fig 5)

- Heat storage causes on-off behaviour on electricity production of CHP plants in the *FI_R_Urban* area. We see differences compared to smoother production levels, which seem to have a similar shape as heat demand, when heat storage is no available.
- The on-off behaviour is seen especially in category of ST-B (Steam turbine back pressure plants)
- Electricity production of CHP plants in scenarios including heat storages does not stay constant for more than a 24 hour-period
- Moments for heat storage to start charging/discharge seem to be linked to moments when ST-B plants start/go off.
- The electricity produced in *FI_R_Urban* area with CHP totals higher in scenarios when heat storages are available. According to results, supplementary electricity is at least partially compensated by decreasing hydro power production in Nordic level, resulting in smaller import from Sweden in intra-day markets.

5.1.2 Nordic-level impacts

Since the version of Wilmar JMM optimizes the expectation value of total costs of electricity and heat supply over the area of Nordic countries (Norway, Sweden, Finland, Denmark), the impacts of heat storages in increased wind power share environment are not necessarily restricted to Finland. We also explored the electricity supply in Nordic level to find characteristics of SGEM scenarios.

With regard to annual values of coal, hydro, and natural gas based electricity production, virtually no differences were found between scenarios as the hourly productions are summed. The total production of hydro power is slightly smaller in scenarios, where heat storage is optional. It is interesting to notice that in reference scenario[2] with conventional electricity supply structure, the electricity production from coal is 32.1 TWh and from wind 4.9 TWh. Thus, the SGEM characterized scenario decreases the amount of used coal and the corresponding CO_2 emissions.

Table 3. Annual production by fuel in the Nordic area (TWh) in No storage, Double storage and reference scenarios by selected fuels.

	No storage	*Double storage*	*Reference*
Coal	21.0	21.0	32.1
Natural gas	14.6	14.7	11.4
Hydro	182.7	182.6	204.1
Wind	41.1	41.1	4.9

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[2] Please note that stochastic optimisation mode was in use Reference scenario (default setting of the modelling system when installed), whereas the deterministic mode was used in the other scenarios. This may have an impact on comparability of the Reference scenario results to other scenarios.

Also in Nordic level, the variations in simulated *hourly* production patterns can be observed, however. Fig 7 presents an example of coal-based electricity production in January, where a difference hourly production between scenarios at a maximum of a range 500 MWh can be observed. It was found out that the fluctuations in coal use seem to be linked with water use. That is, when production in a scenario is higher due to the coal use, the water use is smaller and vice versa.

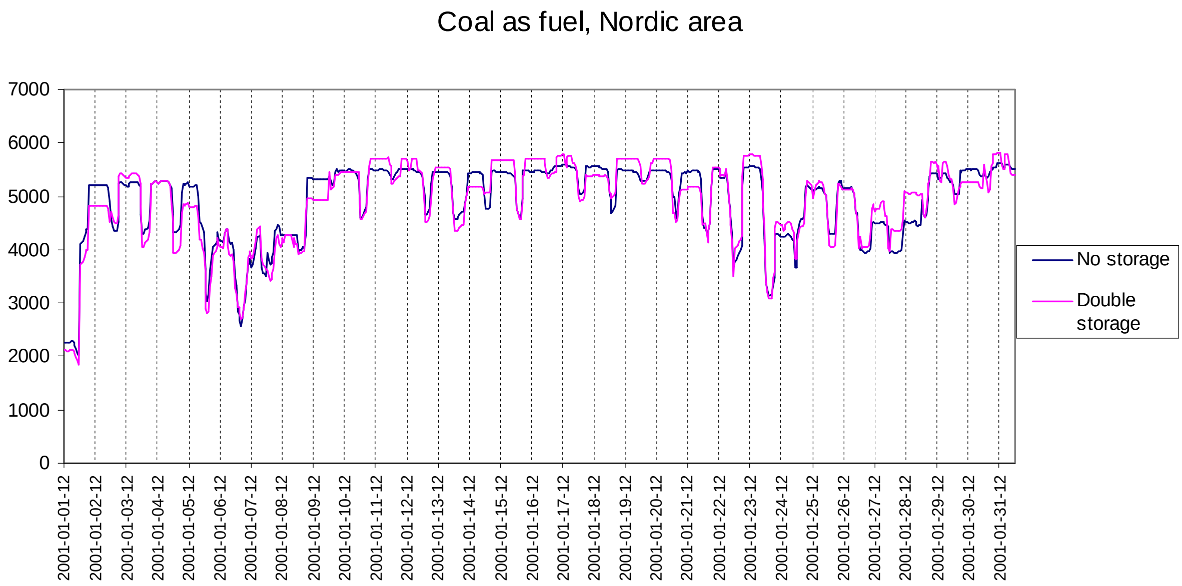

Fig 7. Coal fuelled electricity production in Nordic area (MW), January, No storage and Double storage scenarios.

Table 4 shows the results “TotalCosts” query of the different scenarios. This covers both the total system costs plus change in hydro power reservoir value (Kiviluoma & Meibom 2006).

Table 4. Total costs in the scenarios according to TotalCosts query. ***Note: the functionality of queries should be better verified due to potential infeasibilities in optimization. This indicates the results presented here are of low reliability.***

Scenario	TotalCosts	Relative difference to No storage scenario
No storage	5.855E+09	0 %
Single storage	5.895E+09	+ 0.7 %
Double storage	5.886E+09	+ 0.5 %

According to the results, the total costs of the ”No storage” scenario are the smallest. This seems surprising since one would suppose the largest total costs are not achieved any scenario with more storage optional (at no cost). However, in heat storage scenarios, the operational reliability of the energy system may be higher, which is not directly reflected in costs

The differences are relatively small and seen only in the third decimal. Relatively, the costs of the Single storage scenario are 0.7 % higher than the total costs of No storage scenario, and the costs of Double storage scenario are 0.5 % higher.

The potential explanations for the observation on costs include:

- The optimum obtained represents an estimate due to
    - Different method and timescales of the MH model (water values) and JMM optimization. Thus, the computational estimate of the water values from MH model may not correspond the theoretical value.
    - Limited solution times - the optimisations are artificially stopped after a preset time is reached.
    - Random effects in stochastic optimisation (MH model) between runs.
    - Errors and non-feasibilities in runs.
- In sequential optimization, a modelling system with these characteristics can give results which are not theoretically supported by the set-up of assumptions
- The scale of the storages in scenarios is rather small in the whole Nordic energy system. This makes the effects that bias the results more dominant.

5.2 Discussion

The observed on-off operation of CHP in storage scenarios is most visible in steam turbine back pressure plants. Due to its characteristics, heat demand normally determines the operation mode of this plant type. Thus, on a basis of model results it seems that with the aid of heat storage, running the plants in more variable mode, including charging and discharging storage, lowers the short-term operation costs of the whole energy system.

The on-off effect did not produce substantial differences in annual costs or production volumes in the whole Nordic system level. The costs were, surprisingly, slightly larger in storage scenarios. However, the reliability of this result should be further verified.

No clear pattern for the behaviour of heat storage charging and discharging is observed. This is explicable by the fact that the use of heat storage is driven by several factors (Kara et al. 2004)

- Outdoor temperature
- Price level of electricity; the difference between prices at day and night times
- The day-night variability of district heat demand

- Utilization rate of CHP unit
- Charging level of storage

According to a review of results, there are indications of a following pattern:

- Heat storage is charged, when CHP plants of *FI_R_Urban* area are run in full mode (most notably increased fluctuation is observed in steam turbine back pressure plants).
- Storage is discharged when these plants are turned off.
- The increasing fluctuation in electricity production of CHP plants is regulated by hydro power in Nordic level.
- The amount of wind power available is a potential explaining variable for the observed pattern. If there is lots of wind power available, a supply need for other plants is lower. With a storage option in use, a fluctuation seems to be cost-efficiently matched by more cyclical use of CHP plants. However, this assumption is not fully confirmed and needs to be further studied.

The results of JMM are based on day-ahead optimization with the deterministic mode in use. Thus, an observation of usual 24-hour periods in simulated usage of CHP plants is reasonable. However, in the real world, the amount of realising wind power production of the following day is not certain. Deterministic mode, assuming perfect information of the realising wind power, excludes the effects of non-predictability of increased wind power, which may etc. increase intra-day volumes. The deterministic mode may also contribute to the observed on-off type of operation of CHP plants in the results.

According to Kara et al. (2004), 17 315 MWh of heat storages is installed in Finland. Thus, the maximum of 10 560 MWh of storages modelled in the *FI_R_Urban* area in the scenarios represents a conservative estimates of changes brought by SGEM technologies. Therefore, a larger scale inclusion of heat storages or other SGEM technologies - possibly in other areas and Nordic countries as well - might be worth studying to get the effects more visible.

In the model results, heat storage was found to be included in SGEM characterized scenarios with more wind power, but the scenario framework did not include an option where its use in current-type system was studied. Relatively long calculation times of JMM-MH model system (~20 h/run) limits the practical possibilities to test, scan, and analyse large variety of scenarios in this study. However, as discussed in this section, plenty of issues remain as interesting topics for further studies.

6 Conclusions

In this study, the goal is expressed as to *study the effects and significance of Smart Grid technologies in (future) energy systems.* The topics are approached by computational model based scenario analysis. Feasibility of available model tools is discussed and test-type of runs with the model are conducted to explore the properties of a SG type of energy system.

6.1 Consideration of models

We explored the system and preliminary tested the suitability of available energy system models with respect to the goals of this study. In the end, the candidates for this study turned out to be TIMES-VEDA and Wilmar Planning Tool based models.

It was decided that a recent modification of Wilmar Planning Tool (Rinne 2011), utilizing MH model of VTT, was applied. The decisions implicated that traceability and micro-level demonstrability of the scenarios are of high priority. On the other hand, system-wide long-term evolution and macro-level effects might have been better tackled with TIMES-VEDA based scenarios.

6.2 Definition of scenario characteristics and assumptions

Of large variety of technologies discussed in SG context, the scenarios explored the effects of the following technologies in the Nordic energy system:

- increasing amount of wind power and
- the role of heat storages

These choices are supported by technological maturity and the anticipated significance of wind power in meeting the renewable energy targets by EU in the Nordic countries. The amount of wind power in the Nordic countries was scaled to represent the targeted or achievable capacity of 2020. The differences between the assumptions in scenarios were kept simple and small, aiming to preserve the traceability and fluent exploring of scenarios.

6.3 Result of the scenario runs

Most notably, differences in CHP plant use in the *FI_R_Urban* representing urban heat area of Finland, was observed between scenarios.

- Heat storage causes on-off behaviour on electricity production of CHP plants. We see differences compared to production when storage is not available: in these scenarios, the variance in production is smaller and seems to be related with heat demand.
- The on-off behaviour is seen especially in category of ST-B (Steam turbine back pressure plants)

The heat storage of the modelled scale (maximum heat content ~10 000 MWh, charging rate 600 MW) does not seem to have noticeable major effect on Nordic-wide annual energy balance.

6.4 Significance of the results

Considering the properties of available energy system models, this study provides information of their suitability in SGEM related problems.

Defining and testing of scenarios, building on a model version of Wilmar Planning Tool developed by Rinne (2011), provided tests of feasibility of new model version in SGEM related problems. Also, the new modelling framework was tested slightly further.

The results of the scenario runs must be seen as preliminary experiments of suitable modelling tools for system effects of SGEM technologies. In the future, validation of the model, updates of power plant stock and constructing more realistic scenarios to obtain more reliable and precise results are of interest. This would include an analysis of broader variety of SGEM technologies in a more realistic environment, giving more concrete results

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