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Scenarios for future power system development in Finland

Y. Majanne *, T. Björkqvist*, M. Vilkko *

*Tampere University, P.O. Box 589, FI-33014 Tampere University, Tampere, Finland (e-mail: yrjo.majanne@tuni.fi, tomas.bjorkqvist@tuni.fi, matti.vilkko@tuni.fi)

Abstract: This paper demonstrates how various part-solutions can be combined in different scenarios for a more climate-neutral electric energy system. The case study is the Finnish electric energy system. Four scenarios are discussed. A base scenario for 2030 consists of already agreed future investments in new energy production facilities by 2022 supplemented by additional consumption and a moderate increase in renewable energy generation. Alongside the base scenario 2030, two scenarios with more ambitious renewable energy targets and flexibility issues are examined. The fourth scenario is for year 2050 analyzing the operational properties of the system with high share of variable renewable generation, flexible loads, and high-capacity energy storages. These scenarios help to assess how, for example, investing in wind or solar production, heat pumps on a large scale or the battery storage of electric vehicles influences the other components of the system and the implications for emissions.

Keywords: Power system modelling, variable renewable generation, hourly based balance of production and consumption, load duration curve, ramp rate

1. INTRODUCTION

Main drivers of energy system transition are climate targets and development of renewable electricity generation and electrification technologies. The energy sector is the largest contributor to global GHG emissions [ClimateWatch 2021], and there is a wide consensus that climate change mitigation requires a fundamental transformation of the energy system. (e.g. [IPCC 2018])

Energy system modelling is key in both understanding the energy transition and decision-making under it. Detailed models and powerful computation platforms help in analysis of trends like intermittent generation and sector-coupling in energy system planning. [Pfenninger et al. 2014], [Helistö 2019], [Subramanian 2018]

Transition to a carbon free energy system requires major changes in the power generation and consumption practices. The transition will proceed step by step, because investments in energy systems have long life spans bringing on path dependency and inertia to the transition process. This may be problematic, because in power systems everything interacts with everything, and in many cases, it is not possible to change the system in small pieces, but a bigger one-off change will be needed. On the operational point of view, one of the biggest challenges is the utilization of the variable renewable energy (VRE) generation as the main power production method, and still maintain a momentary power balance between the production and the consumption. VRE generation ousts controllable generation, typically thermal power plants, and at the same time VRE increases fluctuations on the generation side. Thus, increased disturbances in the system should be regulated with reduced controllable generation capacity.

In systems with a relatively small amount of dispatchable power generation, the needed flexibility has to be produced by controllable loads and energy storages. However, outside of a reservoir type hydro power generation and pumped hydro power plants, at the moment there is available no carbon free high-capacity flexible electric power generation and storage processes with feasible price. Nuclear power production is carbon free, but in many countries, such as in Finland, for security reasons legislation does not allow nuclear units to be operated actively as controllable generation units, but they must be operated as base load plants. However, in future, this may be changed. From the economical point of view it is also most feasible to operate nuclear units with maximum capacity, because the variable operation costs are small compared with fixed costs.

In solving the operation problems of power systems with high VRE share, increased interconnector capacity between neighbouring countries will be needed to balance the operation of the power system. The idea is that fluctuations caused by local VRE generation will be smoothed by interconnection of wide area VRE generation.

This paper presents four scenarios, three for year 2030 and one for 2050, about different transition paths of the Finnish power system towards the carbon free system. The main question of the scenarios is, how different combinations of power system properties affect the operability and security of the system. The scenarios vary capacities of VRE generation in the system, heat pumps replacing CHP generation in heating of buildings, electric vehicles interacting with the power system, thermal and electric storages, and flexibility in industrial electricity consumption.

Chapter 2 presents the modelling tool and the developed model of the Finnish power system used for simulations of

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different scenarios. Chapter 3 introduces the studied scenarios. Chapter 4 presents the results how different structural combinations affect the operability and reliability of the system. Chapter 5 concludes the results and discusses what should be kept in minds, when designing the transition pathway to carbon free renewable power system.

2. MODELING OF THE POWER SYSTEM

This chapter describes the applied FlexTool modelling and simulation tool and the structure of the developed model of the Finnish national power system.

2.1. IRENA FlexTool modelling software

FlexTool is a free software provided by the International Renewable Energy Agency [IRENA 2018]. Model configuration, required input data, and results are presented as Microsoft Excel® tables and charts. The applied solvers are the freely available COIN-OR's Linear Program Solver (CLP) and GNU's Linear Programming Kit [GLPK].

The principled structure of the model is presented in Fig. 1. The model consists of energy grids, such as electric and heat grids. The grids can be connected with each other by energy conversions converting e.g. electric power to heat power by a heat pump, or by generating electricity in a CHP heating power plant. The grid consists of nodes consisting further of different generation types with their capacities, constraints, and costs, storages, and loads. The nodes are connected to each other by transmission lines having defined transfer capacities and losses.

Profiles for loads and VRE generation are defined as time series. The model can be run in a dispatch mode or in an investment mode. In the dispatch mode the tool defines the cost optimal operation schedule to the generation capacity defined by the model. In the investment mode the FlexTool designs cost optimal generation system capable to fulfil the required load demand.

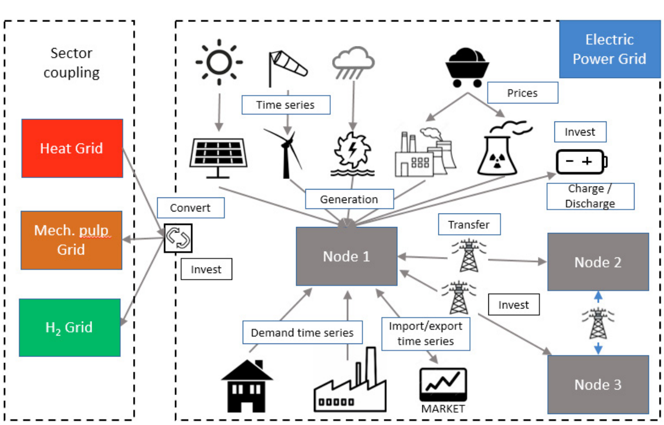

Fig. 1. Structure of the FlexTool model consisting of different grids and nodes within the grids, aggregated generation units, consumption, and transmission between nodes. Modified from [IRENA].

2.2. Finnish National Power System

Power production in Finland is mainly maintained by nuclear, hydro and thermal generation. Thermal generation is combined heat and power (CHP) production consisting of industrial and municipal CHP plants producing process heat and district heat respectively. On 2020 electricity consumed in Finland, 82 TWh, was produced by: 28% by nuclear generation, 19% by hydropower, 22% by CHP generation (12% from heating and 10% industrial power plants), 10% by wind power, 3% by condensing power, 0.3% by solar power, and the rest, 18 % was imported.

The model of the Finnish power system developed in this project consists of two main grids, the electric and heat grids, and two auxiliary grids: the pulp grid and the hydrogen grid. The two auxiliary grids are applied to model future demand response characteristics in the industrial sector.

The electric grid model consists of three nodes: the national transmission and distribution (T&D) node, the market import node, and the market export node. The T&D node consists of aggregated power generation units and time series for profiles of electricity consumption and VRE production. The electric power generation portfolio consists of non-flexible nuclear generation, hydropower generation divided into the non-flexible run of the river type and flexible reservoir type generation, non-flexible industrial and flexible heating CHP generation (flexibility achieved by heat storages), condensing steam power generation, wind power, solar PV, and gas turbine-based reserve generation. Generation profiles of wind and solar PV generation are based on historical hourly based production time series from 2018 obtained from the Fingrid open data platform [Fingrid Open Data 2021].

The import and export nodes of power market are applied to model market transactions based on the market price of electricity, availability of generation capacity and momentary load. Power transfer capacities between the T&D node and market nodes are limited by the interconnector transfer capacities between neighbouring countries.

The heat grid is divided into two individual nodes, one for the metropolitan area of Finland and the other for the rest of the country owing to their different plans for investing in thermal storages and heat production. Heat nodes are supplied by heating CHP power plants and heat pumps. Heat nodes include thermal storages providing flexibility in the CHP generation and in the operation of heat pumps.

The pulp grid models the demand response capacity in the mechanical pulping industry, which is of decisive significance for the Finnish economy and energy system. Mechanical pulping processes are highly energy intensive with over 600 MW of controllable grinder and refiner power capacity. Overcapacity in pulp production and 8-10 hour pulp storing capacity enables optimal scheduling of the operation of the pulp-grinders and refiners as a function of the price and availability of electricity in the power system.

The hydrogen grid models the effects of future hydrogen economy on the electric power system. Hydrogen is produced by electrolysis of water. The hydrogen grid consists of constant hydrogen consumption, storage capacity and electrolysers for hydrogen production supplied by the T&D electric node. According to plans, the first very high-capacity hydrogen project will be a new hydrogen based iron ore reduction process replacing a conventional carbon reduction process. [SSAB 2022] Changing the whole production capacity of the steel plant to hydrogen reduction process, will require additional annual 7.8 TWh electric energy for hydrogen production. This is almost 10% of the current electricity consumption in Finland.

The price of electricity is important for the operation planning of the power system. The price determines whether in power companies having their own generation capacity, the power will be generated by their own resources or purchased from the market, and whether self-generated power is to be sold in the market or merely self-consumed.

For the modelled scenarios a calculated market spot price is calculated based on the residual load in the power system. In this study, the residual load is defined as the difference between the total electric load and power generated by VRE generation consisting of wind and solar and run-of-the-river type hydro power, plus fixed nuclear and industrial CHP generation. Thus, the residual load is the remaining load which must be continuously dispatched to balance the production and the consumption in the electric power system. The market price correlates strongly with the amount of residual load. The higher the load, that is, the greater the need for dispatchable power, the higher the price. In our model the residual load-based price is scaled to have the same statistical characteristics as the modelled electricity marginal price for the scenario calculated in another task of the same project [Aalto et al. 2021].

3. SCENARIOS FOR FUTURE ELECTRIC POWER SYSTEM TRANSITION IN FINLAND

Energy systems involve large infrastructure based on long-term investment. Even with the target of accelerated transition of the energy system, much of today's up-to-date power system components will still be in place in 2050. This means that the energy system models for future scenarios should be built on the present energy system.

This paper deals with four scenarios. Scenario 1, the base scenario for 2030, is built on the investments already decided on and financed by the end of 2022, and then supplemented with non-radical evolution of consumption and VRE generation. Scenario 2 for 2030 includes increased electrification and adds VRE generation without separate investments for flexibility. Scenario 3 for 2030 adds separate investments for flexibility. Scenario 4 for 2050 adds remarkably VRE generation and flexibility in the system. In all scenarios the interconnector capacity for power import/export is 5000 MWh/h.

The power system model is validated against the situation of 2018 in the Finnish Powe System, which is also used as a reference model. The key parameters and characteristics of the reference model and the scenarios are listed below:

Reference Model 2018: Situation 2018

- Electric load 85.6 TWh_e
- 4 nuclear units (2 800 MW_e) in operation
- Condensing thermal (fossil) 120 MW_e
- CHP Industry 2 800 MW_e
- CHP District heating 3130 MW_e
- Thermal storages 1,3 GW_{th}, 18 GWh_{th}
- Wind power, 2 200 MW, 10.3 TWh/a
- Solar PV, 100 MW, 80 GWh/a
- Hydro ROR, 2100 Mwe
- Hydro RES 1000 MW_e, 30 GWh_e
- Open Cycle Gas turbine reserve units 1 254 MW_e

S1 2030: Moderate increase from 2022 situation in VRE generation and consumption

- Wind & solar PV capacity 6.1 GW & 2 GW
- 525 000 EVs, "Plug and charge"[1]
- 5 nuclear units (4 379 MW) in operation
- 1000 MW_{th} heat power generation moved from CHP to heat pumps
- 1800 MW_{th}, 130 GWh_{th} thermal storages
- 620 MW, 3.4 GWh industrial flexibility (mechanical pulping)

S2 2030: Strong increase in VRE generation

- Wind & solar PV 10 GW & 5.2 GW
- 6 nuclear units (5 594 MW) in operation
- 700 000 EVs, "Plug and charge"
- Additional 1600 MW_{th} thermal power from CHP to heat pumps
- H_2 production 7.5 TWh/a (constant load for steel industry)

S3 2030: Increased flexibility with the same generation capacity as in S2,

- Additional storage capacity in H_2 grid, 8.56 GWh
- 700 000 EVs, "Optimized charging"[2]

S4 2050: Strong increase in VRE generation and reduced nuclear generation

- 2 nuclear units (2800 MW) in operation
- Wind 20 GW, PV 10 GW,
- Heat storages 3.52 GW_{th}, 260 GWh_{th},
- Electricity storages 8.8 GW, 125 GWh (EV batteries, pulp & H_2 storages)
- 2 000 000 EVs (optimized charging)
- Geothermal heating, 500 MW_{th}

Table 1 summarizes the main model parameters in the different scenarios.

[1] Plug and charge: home charging scheduled starting successive in four equal slots between 16:00 – 19:00
[2] Optimized charging schedules home charging between 18:00 – 07:00 minimizing the residual load.

Table 1. Key parameters of reference model 2018 and four scenarios S1 ... S4

Scenario	Load TWh_e	Nucl. MW_e	VRE MW_e	CHP MW_e	Heat Stg GWh_{th}	Elec. Stg GWh_e	EVs 10^6
RM 2018	85.8	2 800	4 434	5 912	16	30	0
S1 2030	94.6	4 400	10 200	5 412	130	33.4	0.5
S2 2030	103.5	5 600	17 340	4 912	130	33.4	0.7
S3 2030	104.6	5 600	17 340	4 912	130	42.0	0.7
S4 2050	109.1	2 800	32 100	4 030	260	124.9	2.0

4. RESULTS

This chapter presents the main results analysed from the simulated scenarios. The operability of the four scenarios are evaluated from the perspectives of sustainability and security of supply. Sustainability is evaluated according to CO_2 emissions and the share of renewable generation from total consumption. Security of supply is evaluated according to market activity and residual load. The scenario models assume that the only limitation on importing and exporting electricity is the transmission capacity of interconnector lines. In practice, this is more complicated, and the temporal import/export capacity between neighbouring countries depends on market situations and weather conditions over the whole market area. The main results of the scenarios are collected in the Table 2.

Table 2. Key results of the ref. model and four scenarios

	2018 RM	2030 S1	2030 S2	2030 S3	2050 S4
Consumption, elec, TWh	85.78	94.57	103.51	104.62	109.1
Generation, elec, fuel+RES hydro, TWh	52.91	61.87	66.40	64.72	39.61
Generation, elec, VRE, TWh	13.77	26.87	39.58	39.61	69.55
Imported electricity TWh	19.10	7.18	4.82	5.66	14.74
Exported electricity TWh	0.002	1.35	7.28	5.38	8.53
CO_2 (Mt), indigenous generation	13.64	8.85	7,01	6.37	0.12
CO_2 (Mt), total	15.55	9.57	7.49	6.94	1.47
VRE share % (indigenous generation)	20.65	30.28	37.34	38.0	63.71
Peak load, GWe	14.07	16.24	19,46	19.08	23.14
Peak residual load, GWe	12.21	13.45	14.56	14.57	14.49

The residual load implies both to the sustainability and to the security of service of the power system. The greater the residual load, the greater the additional dispatchable power needed to balance production and consumption. Before the advent of a feasible technology for large-scale storing of electric energy, this dispatchable generation capacity is preferably hydropower, if available, or in other case fossil fuel-fired combustion-based generation. In the latter case, the sustainability of the power system operation is degraded.

Here, the stability of the residual load matters even more than its amount. The more fluctuating variable generation in the system, the greater the need for controllable generation capacity or demand response to balance the system. In future this may be problematic also in the Nordic power system Nordpool because of the increased control power transfer from the Nordpool to the Continental Europe and the UK.

4.1. Duration Curves for Residual Loads and Marketed Powers

Duration curve illustrates how many hours in year a power flow has been above the curve level. Fig. 2 depicts the duration curves of residual loads and Fig. 3 of marketed powers for all scenarios. In Scenario 1 the residual load is positive about 7800 hours/a, which means that the operation of the S1 system requires additional balancing power almost all through the year. In scenarios S2 and S3, where the amount of VRE generation has been increased from 10200 MW to 17340 MW, the average residual load level has dropped clearly being positive for about 6000h/a. In S1 the average generated residual load is 2.76 GWh/h and in S2 and S3 it is app. 2.62 GWh/h. The corresponding energies are for S1 21.4 TWh and for S2 & S3 15.7 TWh. The amounts of negative residual energy for S1, S2 and S3 are -0.94 TWh, -5.30 TWh and -5.04 TWh. Thus in scenarios S2 and S3 the amount of required positive residual energy is remarkably smaller compared with S1, but negative residual energies are bigger meaning significant amounts of over production.

In S4 the behaviour of the residual load is different compared to other scenarios. The residual load is characterized by high positive and negative residual loads, 12 GW and -10 GW, and the numbers of positive and negative peak load hours are bigger compared to S1, S2 and S3. This means that in S4 the values of residual load are distributed much equally over the whole operation range compared with other scenarios. In S4 the residual load is positive 6261 h/a. The amount of required annual residual energy is 32.01 TWh and the annual negative residual energy is -8.26 TWh.

Fig. 3 depicts the duration curves for marketed electricity. Positive MWh/h values depict importing and negative values exporting. From the residual load duration curve of S1 we found that the residual load was positive for 7800 h/a, and from the duration curve of the marketed power, it can be seen that power is imported 6200 h/a and exported 1636 h/a.

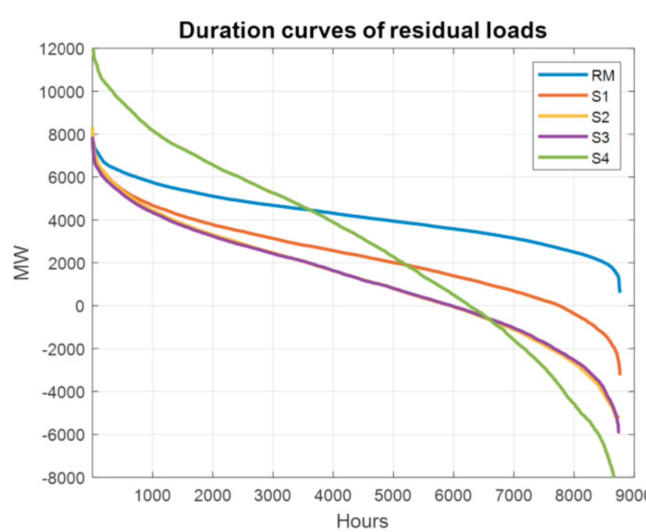

Fig. 2. Duration curves of residual loads of reference model and scenarios S1, S2, S3 and S4.

The average imported power is 1.15GWh/h and the average exported 0. power is 83 GWh/h.

In S1 the total imported and exported energies are 7.18 TWh and -1.35 TWh respectively. In S2 power is imported 3650 h/a and exported 4222 h/a. The average import and export powers are 1.32 GWh/h and -1.72 GWh/h. The total imported and exported energies are 4.82 TWh and -7.28 TWh. In S3 the corresponding average importing and exporting powers are 1.56 GWh/h and -1.54 GWh/h, and energies 5.66TWh and -5.38 TWh. Comparing S2 and S3 it can be seen that increased storage capacity in S3 increases the amount of imported energy but decreases the amount of exported energy. The increased importing of energy in S3 results from the charging of storages with imported energy.

In S4 the utilization of market is bigger compared with other scenarios. It can be seen from the figure that in S4 the interconnector capacity (5000 MW) is fully used in both directions. The average importing and exporting powers are 3.34 and -2.96 GWh/h respectively, and the imported and exported annual energies are 14.74 TWh and -8.53 TWh. Thus, the operation of S4 is highly dependent on the market access.

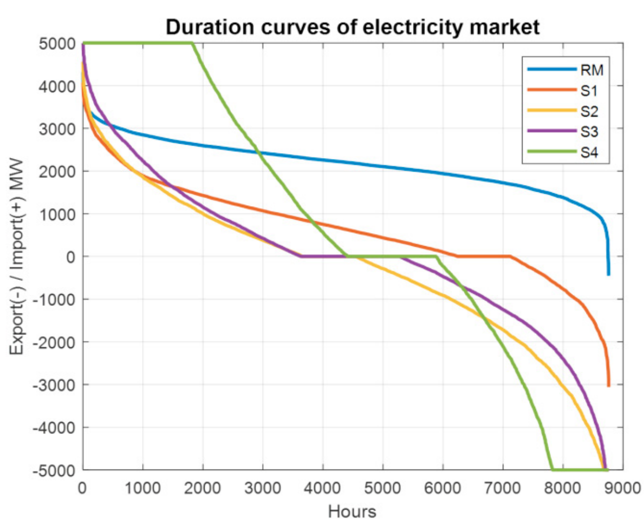

Fig. 3. Duration curves of market activities of reference model and scenarios S1, S2, S3 and S4.

4.1. Ramp rates for Residual Loads and Marketed Powers

Ramp rates illustrates the changes of successive power values characterising the stability of the residual and the marketed loads. Ramp rates are directly proportional to the required control capacity of the on-line generation capacity and flexibility of the market. Figs. 4 and 5 depict the average ramp rates of residual loads and market actions in 12 h time window of all scenarios.

The ramp rates show the effect of VRE generation to the stability of the residual load and market actions. The higher the capacity of VRE generation, the bigger the variability in residual load and market actions, when the market is used to balance the system.

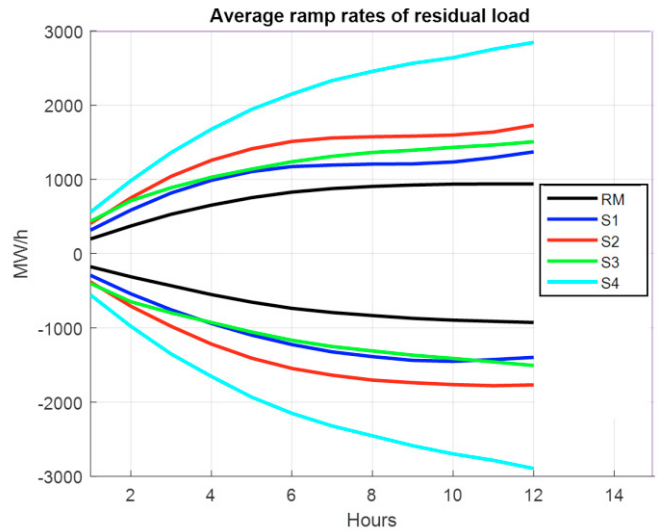

Fig. 4. Average ramp rates of residual loads of reference model and scenarios S1, S2, S3 and S4.

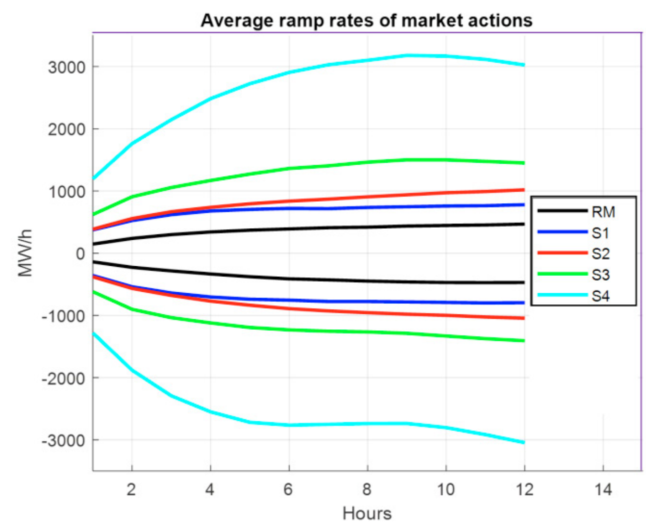

Fig. 5. Average ramp rates of market actions of reference model and scenarios S1, S2, S3 and S4.

The effect of the storage capacity can be seen also from the ramp rates. Especially in market actions, the different amount of storage capacity in scenarios S2 and S3 can be seen from the ramp rate envelopes of market actions. In S3 where the amount of variable generation is equal with S2 but there is more storage capacity on S3, the ramp rates are smaller compared with S2. Ramp rates in S4 are in their own class. Decreased base load generation by reduced nuclear power and CHP generation together with highly increased VRE generation make the system very volatile with highly fluctuating residual load and market actions used to balance the system.

5. CONCLUSIONS

This paper presents the results of a scenario work sketching on how different properties of future power system will affect the sustainability and security of service of power system operability. A common way to improve sustainability of the power system is to replace fossil fuel fired controllable power generation with VRE generation. This has strong effect on the operability of the power system because the variable generation induced disturbances in power balance should be compensated with reduced amount of controllable power generation capacity. In order to be able to balance the future power system, we need more controllable and flexible loads and energy storages.

In this paper we studied the effects of increased storage capacity and flexibility in industrial power consumption, in this case mechanical pulping, to balance the power system. In Finland mechanical pulping industry provides high capacity of quickly controllable loads in several tens of megawatts unit size which can be utilized in power market, e.g. for frequency control. The characteristics of system behaviour were examined by using duration curves and ramp rate envelopes for residual load and energy market behaviour. Those curves gave us information about the capacity and the dynamics of the required resources needed to balance the power system.

In this study, the power market was the main resource of balancing. In the model, the only limitation was the interconnector capacity between neighbouring countries. In real life this is not true, because there are numerous issues restricting power availability in the market beside the transmission capacity. For instance, if the power system structures in neighbouring countries are very similar relying on weather dependent production, it is possible that the weather conditions in all neighbouring countries are unfavourable for power production leading to the short of power. For this reason, it is very important to analyse all the risks derived from the operation environment and invest to sufficient amount of generation reserves.

An important finding was also the effect of increased storage capacity in the behaviour of the system. It is not enough that we have storage capacity in our system, but we must also have excessive generation capacity to charge the storages. In our scenarios the storages were charged largely from power market increasing market activity. This is OK, if there is power available from the market, but if not, we are not able to utilize our storage capacity.

As a final conclusion it is very important to look the whole system when aiming to more sustainable power system. It is not possible to just change one thing, e.g. increase VRE generation and left the rest of the system as it is. We should have a clear vision how our changes are affecting the whole system and be ready to make all the required investments to reach our goals. There is no partial solution available.

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