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WP3: Flexibility and Ramping Requirements

Yifei Guo, Qiuwei Wu, and Qing Zeng

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By

Yifei Guo, Qiuwei Wu and Qing Zeng

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Summary

The report summarizes the study of the flexibility requirement of the future 100% renewable based Danish energy systems by 2050. The source and demand data of energy scenarios from AAU were used as inputs to determine the netload of the future Danish energy systems.

In the first part of the report, the flexibility characteristics of different flexibility options both from the supply side including the hydro power plants, biomass power plants, and CHPs, and from the demand side including demand side management (industrial/household loads), power to heat, and power to gas. Besides, the battery energy storage systems and EVs can provide flexibility support at both supply and demand sides. The flexibility characteristics such as the reaction time, ramping rate, start-up time, operation range are quantified.

In the second part of the report , the flexibility requirement of future Danish integrated energy system with large-scale renewables in 2050 is evaluated based on the data generated by EnegyPLAN.

Content

1. Introduction

This WP is to quantify the requirements of flexibility and ramping capability in the 100% renewables-based energy systems, which includes two parts: 1) Overview of available flexibility options in the 100% renewables-based energy systems and 2) Ramping requirement assessment of the integrated energy systems.

In the first part of the report, the flexibility characteristics of different flexibility options both from the supply side including the hydro power plants, biomass power plants, and CHPs, and from the demand side including demand side management (industrial/household loads), power to heat, and power to gas. Besides, the battery energy storage systems and EVs can provide flexibility support at both supply and demand sides. The flexibility characteristics such as the reaction time, ramping rate, start-up time, operation range are quantified.

In the second part of the report , the flexibility requirement of future Danish integrated energy system with large-scale renewables in 2050 is evaluated based on the data generated by EnegyPLAN.

2. Flexibility and Resources in Integrated Energy Systems: Opportunities and Challenges

This task provides an introduction to potential demand- and supply-side flexible and ramping resources and their capabilities in integrated energy systems (including electricity, gas, heat, etc.). The 100% renewables-based energy systems require a large amount of support of flexibilities and ramping capabilities from different sources.

At the supply-side, the flexibilities and ramping capabilities can be provided by dispatchable generators, such as hydro power plants, biomass power plants and CHPs. At the demand-side, the flexibilities and ramping capabilities can be provided from different sectors in the integrated energy systems, such as shiftable industrial loads, shiftable household appliances, electric vehicles (EVs), HPs, district heating with heat storages, and power to gas (P2G) stations. Battery energy storage systems (BESS) and EVs (allow V2G mode) can provide flexibilities and ramping capabilities at both supply- and demand-side.

2.1 hydropower

Hydropower is a cost-competitive and low-carbon energy source that provides the full range of services required by the bulk power systems. Generally, hydropower is considered as a flexible power source which has quick-start capability and rapid-ramping capability.

The start-up time of a hydropower plant takes several few minutes, much faster than other conventional power plants such as coal-fired power plants. According to the practical operation experiences, the offline hydro power generation is able to connect to the grid within 10 min [1].In [2], the typical hot start-up time is given as 0.1 h. The quick-start capability entails the hydropower plants are able to synchronize quickly and provide the non-spinning reserves.

Similarly, the hydropower plants have excellent ramping capability, which is only limited by the need to control the water-hammer events in the penstock. The hydropower plants can ramp quite rapidly, of which a typical ramp rate is 15%/min. It reacts to the unexpected load changes in the system within a few seconds. It also has the broad operation band, which is normally 60%-80% of the nominal power. The minimum load is around 5% [2]. The high ramping capability and broad operation band results in an excellent spinning reserve option.

Moreover, different types of hydro power plants have quite different flexibility performance from the time frame perspective. For the impoundment or reservoir-based hydropower plants, which use a dam to store river water in a reservoir, are generally large-scale [3]. They can provide the larger flexibility and storage capabilities and are considered to be flexible seen over a time horizon spanning several months [4]. In contrast, the run-of-river hydropower plants offer no or very limited flexibility and storage capabilities, often with a very small short-term storage possibility of a few hours only [3].

2.2 Biomass

Biomass is a versatile energy source that can be used for production of heat, power, transport fuels and biomaterials, which will play an important role in future 100% renewable energy-based system. Feedstock for biomass energy plants can include residues from agriculture, forestry, wood processing, and food processing industries, municipal solid wastes, industrial wastes and biomass produced from degraded and marginal lands. The utilization ways of biomass energy can be roughly categorized as [5],[6]:

1) Co-firing of biomass in an existing coal or natural gas power plants.
2) Rebuilding coal power plants to biomass plants.
3) Combined heat and power provision only by biomass-fired plants.

For the former two ways, the flexibility such as ramping capabilities, minimal load and start time of biomass plants largely depends on the original plants, related to the original facilities such as boilers. For instance, a biomass plant with the input of wood chips is rebuilt from a coal fired plant. The ramping capability is about 5%/30s for the primary load support and 4%/min for the secondary load support. The minimal load is 10% of the full load. The cold start time from for pulverized fuel and circulating normally varies 8-15h [5]. For the bubbling fluidized bed units, the load-following capability, depends on the startup, ramp, and shutdown time requirements as shown below. 1) From cold shutdown to maximum lo ad, 12h; 2) From hot shutdown to maximum load, 5h; 3) From minimum load to maximum load, 1h; 4) From maximum or minimum load to zero, 0.5h; 5) From synchronization to maximum load, 2h [7].

The biomass-based CHP plants provide reliable, efficient, and clean power and heat, which will be introduced in the following section regarding CHP together with other types of CHP plants [8].

2.3 Combined Heat and Power

Combined heat and power (CHP), also referred to as cogeneration, describes the simultaneous generation of electricity and useful heat. It significantly improves the overall utilization of fuel by substantially reducing the amount of waste heat.

2.3.1 OCGT/CCGT-CHP

The open-cycle (simple-cycle) gas turbine or combined-cycle gas turbine can be operated in CHP mode. The typical fuels of OCGT and CCGT are nature gas light oil [5]. Moreover, the renewable fuels such as biogas can be also used as the fuels for them. The basic flexibility parameters including the ramping capabilities, minimum load and start-up times of OCGT and CCGT are illustrated as the following table [5],[8],[9].

Table 1 Flexibility parameters of OCGT and CCGT

Parameters	OCGT	CCGT
Ramping rate	10-20%/min	4-15%
Minimum load	20-50%	30-40%
Hot start-up time	5-10 min	50-85min
Cold start-up time	5-30 min	2-3h

Ramp capabilities of CCGTs are limited to prevent thermal stress in the heat recovery steam generator (HRSG) components and steam turbine. In conventional CCGTs, the gas turbine is ramped to hold points to allow steam temperatures and pressures to rise slowly within allowable material limits. Of particular concern are thick-walled components such as the high pressure steam drum, which could experience thermal fatigue if temperature and pressure increases too rapidly [10].

To be noticed, the technical capability is the technical parameters regarding power generation. However, the CHP plants are often operated in heat-controlled mode. To ensure a constant supply of thermal energy to their customers, they are required to run at a certain load ("must-run capacity"), making them less inflexible. This means that they are limited in responding to changing power demands. Some CHP plants are equipped with thermal energy storage facilities which permit electricity and heat production to be partly decoupled timewise and consequently enhance the flexibility of the CHP plants, allowing the cogeneration plants to react flexibly to changes in power demand.

2.3.2 Biomass CHP

For the biomass CHP plants, the major components includes fuel treatment and feed-in system, high-pressure steam boiler, steam turbine, generator and flue-gas heat recovery boiler (hot water or steam). The biomass fuels could be residues from wood industries, wood chips (collected in forests), peat, straw and energy crops, etc.

The medium (10-50MW)/small (1-10 MW) size biomass plants with drum type boilers can be often operated in the range of 40-100% load and he ramp rate is about 4%/min (wood chips). Moreover, the biomass CHP plants are often equipped with heat accumulators, which allows the plants to be stopped daily. Though the plants can be down regulated, due to the high initial investment of the biomass CHP plants, the plants are preferable to operated in base load [5], [11].

2.3.3 Stirling Engine

Stirling engine fuelled with gasified biomass is a special way of cogeneration. The Stirling engine is filled with a working gas, typically Hydrogen or Helium, and pressurized. A solid biomass fuel such as Wood chips, industrial wood residues, demolition wood and energy crops is converted into producer gas, which is led to one or more combustion chambers, each coupled to a Stirling engine. The gas is ignited in the combustion chambers and the flue gases are heating the Stirling engines, driving an electricity generator. The heat load can be changed in the range of 10-100 % within a few minutes. The electrical output cannot be regulated quickly [11].

2.3.4 Waste-to-Energy CHP

Waste-to-Energy technologies consist of any waste treatment process that creates energy in the form of electricity, heat or transport fuels from a waste source. Several types of waste can be used for waste-to-energy plant: solid (e.g. municipal solid waste (MSW)) [11], semi-solid (e.g. thickened sludge from effluent treatment plants), liquid (e.g. domestic sewage) and gaseous (e.g. refinery gases) waste where the MSW is the most common waste source. The current most known waste-to-energy technology for MSW processing is incineration in a CHP plant [12].

Typically, the waste-to-energy plants should be operated at full load during all operation hours as a base load unit within the electricity generation mix. Actually, the waste-to-energy plants can be down regulated to about 50% of the nominal capacity, under which limit the boiler may not be able to provide adequate steam quality and environmental performance. For emissions control reasons and considering the high initial investments they are preferable to be operated as base load. A given typical minimal load of a waste-to-energy CHP is about 75% of the full load [11].

2.4 Demand Side Management

For the purpose of balancing supply and demand in the power systems, flexibility from demand side can provide the same service as the supply side as long as the demand side can be properly regulated and controlled. Demand side management could provide flexibility on multiple time scales, ranging from seconds to seasons by offering ancillary services (regulation, load-following, contingency). Market designs that emphasize the performance requirements can easily accommodate demand response which is typically capable of providing flexibility [13].

2.4.1 Demand Management of Industrial Load

Industrial demand is shaped by the characteristics of specific industrial processes, and can vary among industries. Some industrial installations involve processes that offer a level of flexibility--

the potential to shift energy requirements of the process in time. Some typical industrial load and their typical ramping times are concluded in the following table [14].

Table 2 Typical industrial loads and their response ramp time

Resource	Response ramp time	Resource	Response ramp time
Packaging	5 min	**Weaving**	5 min
Chiller	30 s	**Catalytic Cracking**	30 s
Wrapping	5 min	**Mixing**	30 s
Sawing	5 min	**Mill**	5 min
Planning	5 min	**Electric Furnace**	30 s
Chipper	5 min	**Crushing**	5 min
Dewatering Press	30 s	**Crushing and Clas-sifying**	5 min
Electrolysis	30 s	**Metal Cutting**	5 min
Compressor	30 s	**Final Assembly**	30 s
Grinding	5 min		

2.4.2 Demand Management of Household Load

The statistics of electricity consumption of Danish households is illustrated in the following figure. The largest share of electricity demand is refrigerators/freezers with the proportion of 18% followed by washing equipments (e.g. washing machine, dryer, and dish washer).

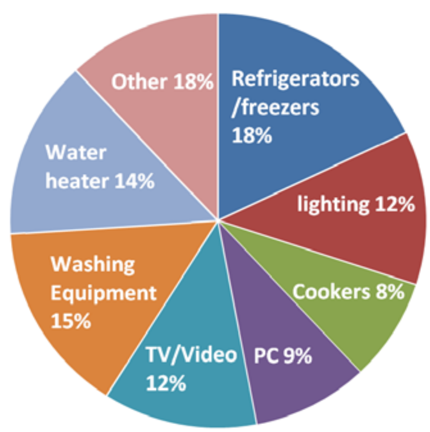

Fig. 1 Electricity demand by category in Danish households [14].

These electric demands are influenced by different factors. For the lighting, cookers, PC, and entertainment (TV/Video), they highly depend on the consumers' behaviors, which cannot or should not be shifted. For water heater for domestic hot water, it depends on the consumers' behaviours but they can be postponed within limited range and without intermittency. The typical shifting time is 15-180 min. For the washing equipments, the demand can be postponed within moderate range. The typical shifting times are 150 min for dish washer and 180-540 min for washing machine [15]. For refrigerators/freezers, Some products are more sensitive to temperature than other products, and even with the same purpose of maintaining a low temperature level, there is difference in temperature tolerance levels. Apart from temperature, sensitive contents which have small temperature tolerance range, refrigerators/freezers can be flexibly operated [15]. The typical shifting time is 15-120 min [16]. The reaction time of the household appliances are generally very quick [8].

2.5 Electric Vehicle

The EV is considered as a promising alternative to conventional internal combustion engine vehicles around the world since it can not only reduce the green house gas emission from the transportation sector but also utilize excessive electric power from renewable energy sources [17]. The EVs can provide system flexibility from both demand side (Grid-to-Vehicle, G2V) and supply side (Vehicle-to-Grid, V2G) [8] .

1) G2V mode: EVs re operated as a demand side management option, forming a flexible electricity consumption supporting renewable power integration.
2) V2G mode: EVs are operated as distributed energy resources. The batteries of EVs could be discharged and feed power to grid, forming large-scale distributed electricity storage regulated/controlled by the needs of electric system.

Since EVs can deliver high power within seconds with short duration time, they are capable of providing primary reserves [18]. Due to the primary use as means of transportation, provision of flexibility could be limited by many factors and it is inherently uncertain. From the utility perspective, proper incentives will likely be needed to ensure that large-scale deployment of EVs does not increase the need for new generation, transmission, or distribution capacity. It can be expected that significant EV deployment can provide system benefits when charging/discharging can be controlled while they have significant negative impacts if not controlled [19].

2.6 Power to Heat

Electricity can be applied to replace other conventional fuels such as coal, oil, and natural gas for heating purpose. Flexible operation of the power-to-heat (P2H) facilities can help to balance the power fluctuations of renewable power generation and thus contribute the integration of renewable power generation, which has been have been propagated as a potential tool to enhance demand-side flexibility and to interlink power and heat markets [20]-[22].

2.6.1 Electric Boiler

A common option of P2H is the direct resistive heating of which the flexibility is provided by selectively energizing heaters and storing the generated heat for later use [8]. The resistive heating comes in the form of electric boiler, which uses the electricity for the production of hot water or steam for industrial or district heating purposes. Another heating element option is electrode which also consumes electricity, which is used for large applications with the typical appliances being 5-50MW/unit [5].

Electric boilers can be controlled to participate in up- and downward regulation. Modern electrode boilers have a minimal standby consumption when used as frequency-controlled reserves (down regulation). The standby consumption varies with the type of electric boiler. New electrode boilers of e.g. 12 MW have electricity consumption down to a few kW and no consumption at high voltage. The electrode boilers operate in such a way that the voltage is kept in the boiler, without applying any power. Using this technology, the only “stand-by consumption” is related to internal pumps and electric boilers can start with close to no standby consumption. Considering the close to none standby demand, many plants chose to keep the boiler operating in standby mode in order to be able to utilize the electrode boilers immediately when necessary. Moreover, it is possible to offer regulating power from cold start, hence eliminating the requirement of a standby consumption. This is made possible ramp up times of approximate 5 minutes in cold start situations, typically being shorter than necessary to participate on e.g. the power balancing market. However, due to the above-mentioned minimal standby consumption, operation on electrode boilers in standby is very common. The load shift from 0-100 % of nominal capacity is approximate 30 seconds [5].

2.6.2 Heat Pump

Electric heat pump (HP) is another P2H option which converts electricity to heat in a more efficient way. HPs employ the same the technology as refrigerators, moving heat from a low-temperature level to a higher temperature. In fact, HPs can be reversible and are able to perform heating and cooling functions. HPs can be utilized for industrial processes, individual heating and district heating. They can be roughly categorized according to the operational principles: 1) compression HPs which can be driven by electricity; 2) Absorption HPs which can be driven heat, e.g. flue gas, steam, hot water, and oil. Compression HPs can incorporate the electricity into heating systems in an efficient way in the future integrated energy system where electricity plays a vital role. Compared with electrical boilers, the primary energy consumption is reduced for HPs. The potential flexibility of HPs is mainly determined by the thermal demand, HP size, the storage size, the dynamic system properties [23].

The electrical compression HPs for district heating can participate in the primary regulation and secondary regulation with the ramping rate of 10%/30s and 20%/min, respectively. The minimal load is 10% and cold start-time is about 6 h [5]. As can be concluded, due to today’s market limitation, the large-scale HPs are not constructed for very quick start/stop or load changes. However, the HPs can be able to quickly start or stop by using the adequate secondary water systems and proper control strategies in the future.

For small-scale individual HPs, they have on/off regulation and some are also equipped with capacity regulation, which means that HPs can balance the heat production to the demand continuously down to around 20 % of maximum capacity. HPs for individual heating are able to stop immediately and can reach full power consumption from the stopped state within 1 min [24].

2.7 Power-to-Gas

Power-to-gas-(P2G) is the process of using electricity to form hydrogen or synthetic natural gas which can then be stored, transported, and used later [24], referring to chemical energy storage. The main process consists two steps [8]:

1) Electrolysis splits water into hydrogen and oxygen by using electricity.
2) Hydrogen is combined with carbon to create methane. Owing to limits to the quantity of hydrogen which may be introduced into the gas network, and transported to the storage locations, further natural gas production facilities may be considered for a large-scale P2G program.

The reaction time of P2G could be from seconds to minutes, which means that the P2G plant is able to provide regulating power and primary and secondary reserves [18], [25]. However, regarding the investment in P2G technology, it should be acknowledged that it is a flexibility option that still is at the research and development stage, despite the fact that some of the specific steps in the supply chain have quite mature technologies [26].

2.8 Energy Storage

Energy storage can help utilities manage this variability in variable renewable generation output by providing a broad array of grid services that generally make the power system more flexible, a recognized key to integrating high penetrations of wind and solar. Storage is a broad category of technologies and applications that can help utilities balance power supply and demand by holding energy for later use. Storage technologies are distinguished primarily by capacity and discharge time. Different storage technologies can be used for each of three main electric sector goals: energy management for daily/hourly scheduling, operating and ramping reserves for load following, and frequency response and regulation to maintain power quality [27].

Here, several typical energy storage technologies including pumped storage, batteries, compressed air energy storage (CAES), flywheel, electric vehicle, and electrolysis, their response time and (potential) suitable applications on different time scales are shown in the following table [8], [18], [28]-[32]. The primary reserve corresponds to the time scale of few to 30 s and secondary reserve corresponds to the time scale of 15 min.

Table 3 Comparison of different energy storage technologies

Storage technologies	Response time	Suitable application
Pumped hydro	Few seconds	Primary reserves, secondary reserves, hours, days
Batteries	< seconds	Primary reserves, secondary reserves, hours, days
Flow batteries	< seconds	Primary reserves, secondary reserves, hours, days
Electric vehicle	Few seconds	Primary reserves, secondary reserves, hours
CAES	9-12 min	secondary reserves, hours, seasonal
Electrolysis, SOFC, hydrogen storage in caverns	Few seconds to minutes	Primary reserves, secondary reserves, hours, days, seasonal
Flywheel	Milliseconds	Primary reserves, secondary reserves, seasonal

Some basic description about these energy storage technologies are given as follows. Electric vehicle and electrolysis for P2G have been introduced in previous sections.

Pumped hydro storage is the most prevalent and mature energy storage technology, which pumps water from a low reservoir using electricity to an upper reservoir by allowing the water to flow back through the generation units to produce power. It has the fast response and ramping capabilities. The new techniques of using underground caverns or subsurface reservoir are opening the possibilities of using pumped hydro storage in an area without mountains [18].

Batteries have been regarded as a mature technology with many commercial MW-scale installations [33]. The lead-acid and the sodium-sulphur batteries are most common for large-scale applications. As known, batteries can react instantly to system disturbances and is able to provide deliver primary reserve. Flow battery is an emerging batter technology which doesn't have any self-discharge, i.e. loss of energy over time of storage, making it more suitable for applications that require long duration than conventional batteries [18].

A CAES operates by means of large electric motor driven compressors that store energy in the form of compressed air in the storage reservoir, normally a underground cavern. For discharge mode, the energy is fed the inlet of a combustion turbine. CAES can be used on very large scales. Typical capacities for a CAES plant are around 50–300 MW. The storage period is long due to the fact that the losses are very small. A CAES system can be used to store energy for more than a year. Fast start-up is also an advantage of CAES. A CAES plant can provide a start-up time of about 9 min for an emergency start, and about 12 min under normal conditions.

By comparison, conventional combustion turbine peaking plants typically require 20– 30 min for a normal start-up.

A flywheel is a mass rotating about an axis, which can store energy mechanically in the form of kinetic energy. Self-discharge rates for complete flywheel systems are high, with minimum rate of 20% of the stored capacity per hour, reinforcing the notion that flywheels are not an adequate device for long-term energy storage but only to provide reliable standby power [30].

3. Quantifying the flexibility and ramping requirements in integrated energy systems with significant renewable penetration

This task quantifies the required flexibility and ramping requirements in integrated energy systems with high renewable penetration. Based on the modeling of the 100 % renewables based energy systems of different scenarios studied in WP1, the fluctuations of the net loads (inflexible loads minus non-dispatchable renewable productions) will be quantified (magnitude and variability). The flexibilities and ramping capabilities are required to balance the fluctuations of the net loads and support the system frequency stability. In the future energy systems with 100% renewables congestions at transmission and distribution level may occur often, which require further support of flexibilities.

The system stability and reliability is also critical in the future energy systems. Due to the reduced inertia of the converter-based renewable energies, system disturbances and/or faults can have a severe consequence to the power systems, such as cascade outage. Therefore the robust and optimal system management and control are important, and the sufficient support of the flexibilities and ramping capabilities is crucial. Modelling and simulations of the future energy systems will be carried out to analyze the system stability and reliability, and the requirements of the flexibilities and ramping capabilities will be quantified in this section.

Electricity demand

According to the future Danish energy system design in 2050, the electricity demand might include the domestic electricity demand, electric boilers, flexible electricity demand, large-scale HPs, individual HPs, EVs, P2G, etc. Some electricity loads are dispatchable according to the integrated system requirement, namely flexibility options, such as the electric boilers, flexible demand, P2G, large-scale HPs, and EVs. Besides, the import/export electricity demand can be also regarded dispatchable based on the marketing mechanism.

Renewable power generation

The renewable power generation in Danish 2050 energy system includes the onshore wind generation, offshore wind generation, PV and wave generation. Here, since we want to know the maximum ramping requirement of the 100% renewable-based energy system under the most severe condition, these types of renewable power generation are all considered non-dispatchable.

Net load calculation and flexibility assessment

The net load can be calculated by,

$$\text{Net Load} = \text{Inflexible Load} - \text{Renewable Power Generation}$$

In this context, we generate the a full-year time series of various demand and supply with the time resolution of 1 hour, using the simulation tool EnergyPLAN. The corresponding results are given as follows,

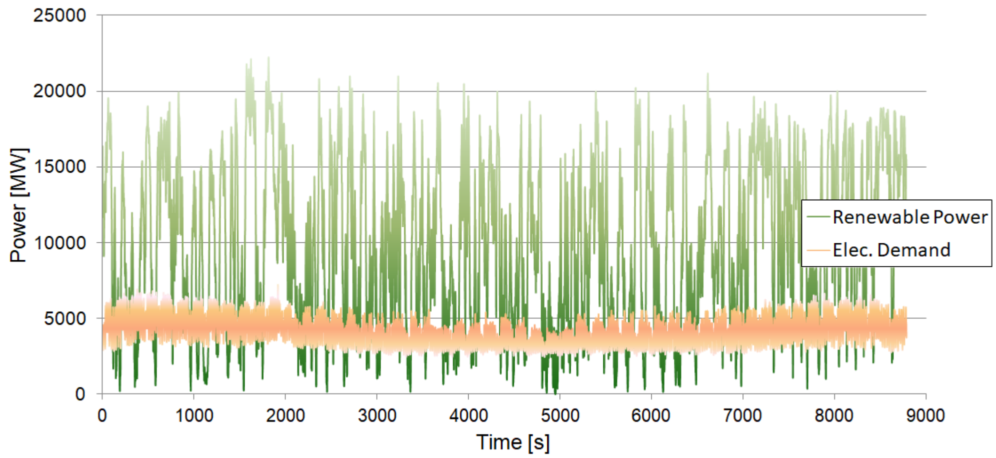

Fig. 1 Time series of renewable power generation and inflexible load.

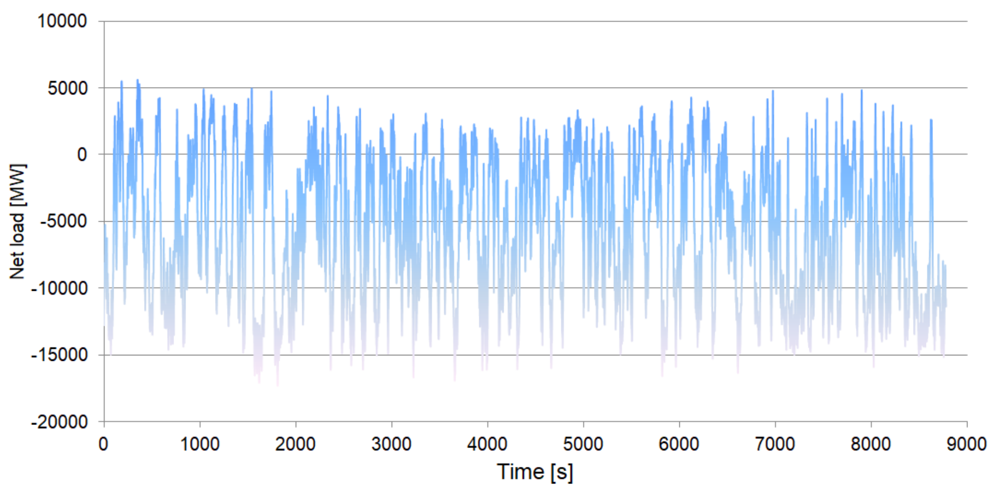

Fig. 2 Time series of net load.

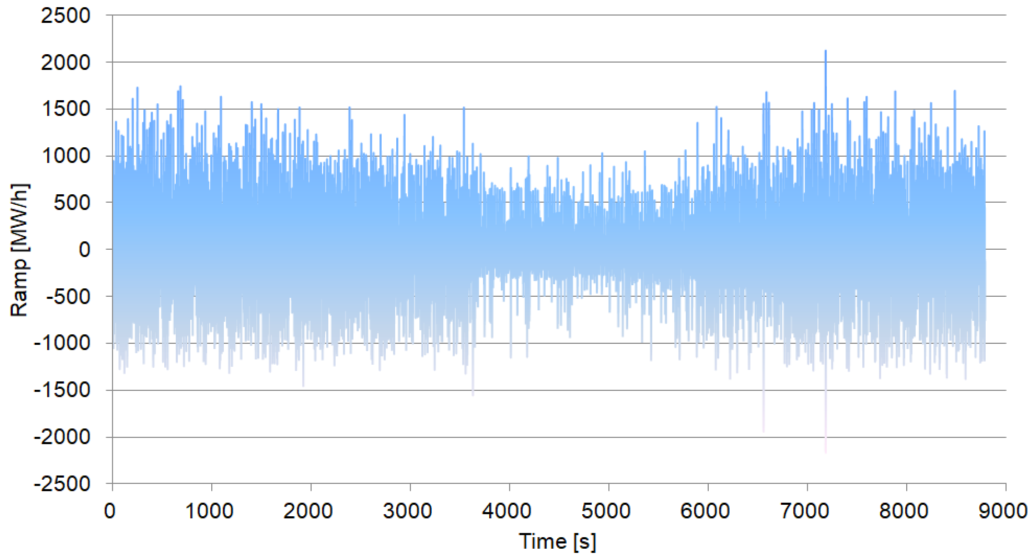

Fig. 3 Ramp needs of electricity load.

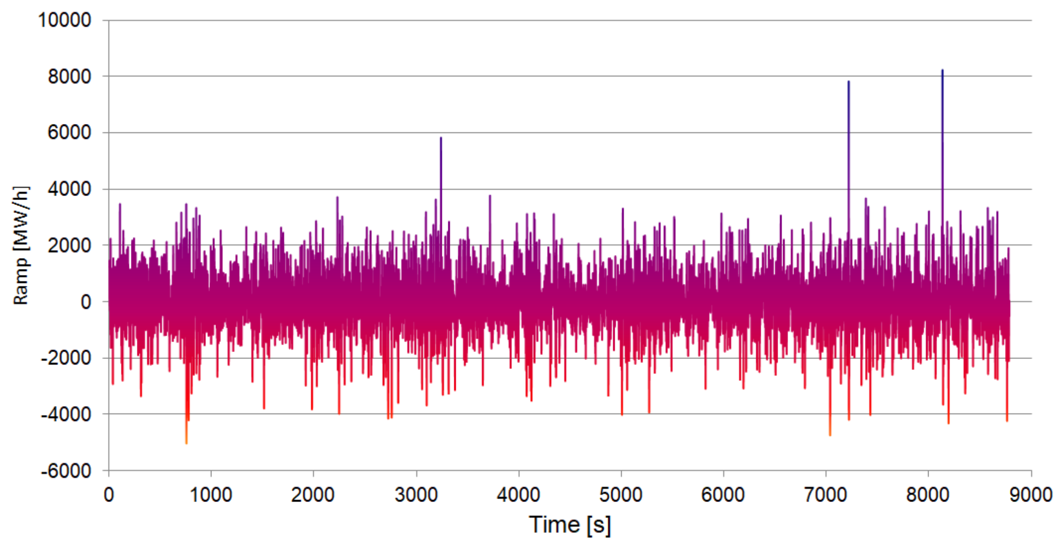

Fig. 3 Ramping needs of the net load with renewable energy.

Table.1 Maximum Ramp Requirement.

	Up-Ramp [MW/h]	Down-Ramp [MW/h]
Only Load	2101	2154
Net Load	8220	5044

Fig. 1 shows the time series of the renewable power generation and inflexible load. Since in the 2050, the installed capacity of renewable power generation is much larger than the load, the net load is often negative as illustrated in Fig. 2, which means that the overproduction of electricity should be balanced by other ways such as energy storage, P2G and P2H.

Fig.3 and Fig. 4 show the ramp time series with load and net load over a year. From Table. 1, it can be observed that the maximum ramping requirement of the system without considering the renewable power generation are 2101 MW/h for up-ramp and 2154 MW/h for down ramp, respectively. However, for the net load, requirements reach 8220 MW/h for the up-ramp and 5044 MW/h for the down-ramp.

4. Summary

In the first part of WP3, the flexibility characteristics of different flexibility options both from the supply side including the hydro power plants, biomass power plants, and CHPs, and from the demand side including demand side management (industrial/household loads), power to heat, and power to gas. Besides, the battery energy storage systems and EVs can provide flexibility support at both supply and demand sides. The flexibility characteristics such as the reaction time, ramping rate, start-up time, operation range are quantified.

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