Potential of individual heat pumps for renewable energy storage in Smart Grid

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Abstract. Ever-increasing power market and environmental policy enforce growth of renewable power sources. Renewables inflexibility and dependency on weather condition causes periodically imbalance in power system due to the green power overproduction. With the increase of renewable sources, the balancing problems in power system will be increasingly significance issue. It is proposed to use individual heat pumps as a next tool for energy system adjustment support. Power system adjustment will be carried out by active demand side management by intended domestic hot water tanks overheating. The smart grid individual heat pumps setpoints will be switched at community or even country scale. The strategy allows shaving the overproduction peaks through short-term increase of electricity consumption in remote controlled heat pumps and to lowering power demand during green power deficits using the thermal energy stored in overheated domestic hot water. The dynamic mathematical simulations were made to define the operation and limitation of active control strategy of heat pumps integrated into smart grid. The results allow testing and assessing the potential of individual heat pumps as a next tool for balancing the power system with large scale of renewable power.

1 Introduction

Worldwide power market steadily growing driven by ever-increasing electricity demand. Maintaining the economic growth and national power security decoupled from the associated environmental pressures are the nowadays issue which are mainly deployed and implemented through increasing share of renewable energy sources. At present, wind power is the leading source of renewable energy [1]. In sustainable power system the renewables are complemented with conventional combustion power, CHP or nuclear plants. Such energy policies lead to the challenge of balancing electricity demand and supply from specific power sources. Increase of green power will indicate overwriting the control and management strategies. Applying the smart grid technologies allows maintaining balance in community, country or even region power system.

The electricity overproduction risk mainly depends on energy power sources mix. The higher share of renewables and lower operational flexibility of conventional sources, the greater risk of overproduction. Despite the growth of world homogeneity each country

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is characterised by different electricity generation technologies mix. On the Fig. 1 are shown electricity production structure by different fuels in 1990 and in 2016, for overall world, European Union Member States and four distinct countries. Germany, Poland, Spain and Sweden represent different fuel mixes and different rates of renewable development between 1990 and 2016. A significant increase in renewables in electricity production is visible, both at the national, regional and worldwide level. On global scale the green power grew of 4.3% amounted more than 3.6 million GWh. At the European Union level, the regional legislation promotes and forced increasing renewables of 20% final energy consumption by 2020 [2].

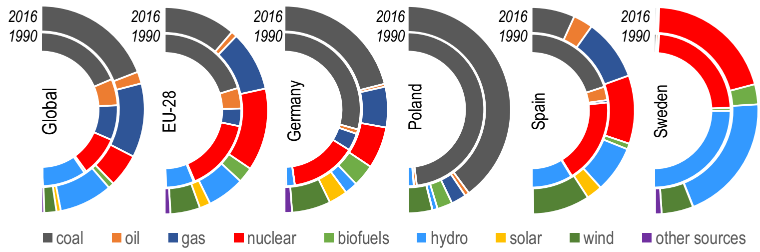

Fig. 1. Electricity production by fuel in 1990 and 2016 [3].

High share of renewable power sources is favourable for mitigation on climate change and power system safety, however, increases the unbalance risk. Renewable sources are majority dependent on meteorological condition and in mostly are complemented with non fast-respond conventional sources (Fig. 2). The long hot start-up time and limited ramping rate of common conventional power generation technologies in combination with inflexibility of renewable power sources require dynamic management and increase electricity overproduction risk.

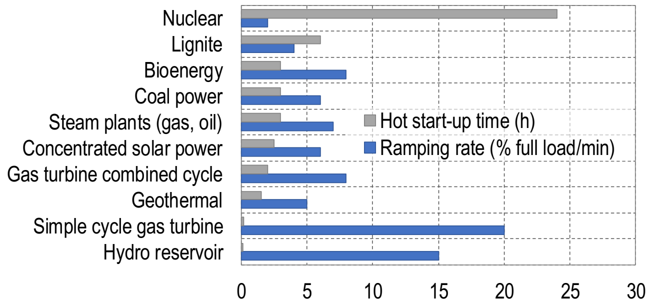

Fig. 2. Flexibility and dynamics of common power generation technologies by fuel [4].

The main goal of current research and development is to solve the problems of excess green energy in power systems. The search areas are focused around smart grid solution in supply and demand management, energy storage and energy conversion. Due to high environmental impact [5], investment and life-cycle costs the effective surplus electricity storage or conversion technologies are still at research and development stage.

Heat pumps (HP) in combination with domestic hot water storage tanks emerge as a favourable and flexible power-to-heat technology for excess electricity storage. Increasing the individual HP market runs parallel to renewable power sources. As shown on Fig. 3 the number of installed HP units in European Union achieved most than 10.6 million in 2017 and is characterised by steady upward trend. More than three quarters of the installed HP are working in standalone installation [6] and a large number of them are fitted with thermal energy storage, mostly for domestic hot water demand.

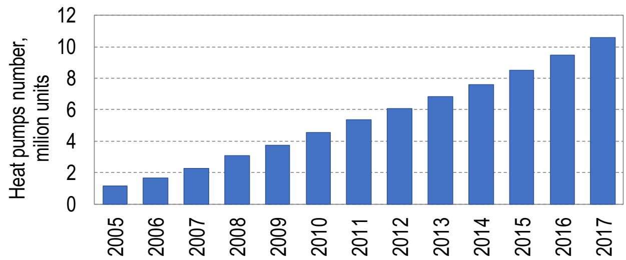

Fig. 3. The number of heat pumps installed in European Union [7].

Millions of installed HP units create a large-scale potential for smart and controlled storage of excess green power in individual water tanks. The smart grid technology will involve the large group of existing and future individual HP in renewable power system active balancing. HP integration into a smart grid creates a new opportunity to remote demand and power-to-heat management in individual HP. Driving the HP units with green power is double-environmentally friendly, zero emission and helps to increase the green power share. In smart grid with green power pricing the heat pumps are profitable both for demand and supply site [8]. In overproduction periods the individual HP units help to balance the power system by consuming excess power in low-price or free energy tariffs. Additionally, the individual HP units are smart grid ready in plug and play technology and are financed by the users. For these reasons the smart grid HP units should be considered as a next tool for active balancing the power system with large share of renewables.

2 Method

The aim of the investigation is to assess the power peaks shaving potential of individual domestic hot water storages supplied by individual HP units integrated into smart grid. The electricity overproduction will be storage as a water sensible heat and utilise during the subsequent domestic hot water demand. The advanced fast-response Smart Grid Control (SGC) strategy remotely changes the setpoint of water storage temperature in periods with electricity overproduction. The SGC changes the setpoint from the user value to the maximum technically or economically justified temperature for analysed HP units. The number of overheated HP is dynamically changed along with the amount of excess energy, considering technical limitations and user safety.

The investigated power system is based on mixed conventional and green power generation on the supply side and large number of individual heat pumps for thermal energy storage in domestic hot water tanks on the demand side. All components are integrated into smart grid to enable supply and demand side communication, remote setpoint control and energy management. The demand on conventional and green power were investigated by numerical simulation for two HP operation scenarios (Fig. 4). Base scenario where each HP unit operates separately based on the own digital controller setpoints. Developed SGC scenario activates an additional power-to-heat storage capacity by smart grid setpoint control, as an additional field of power demand management. The SGC strategy creates scalable power-to-heat storage capacity by integration of individual HP units, for remote switching of stored water temperature setpoints.

For the purpose of the assessment investigated HP units are divided into five groups (from HP1 to HP5) with individual SGC for setpoints control. Small number of groups allows to clearly illustrate the SGC operation principles and assessing the energy storage potential. In the real condition denser division heat pumps on SGC group, the greater adaptation to supply site.

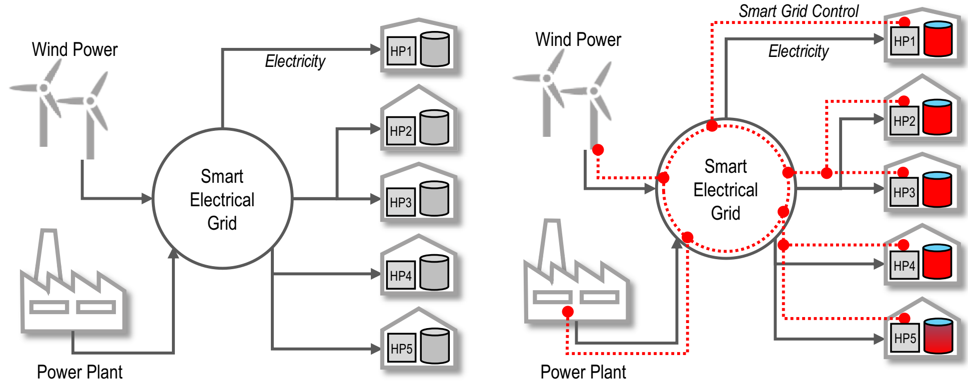

Fig. 4. Investigated power system in base scenario (left) and smart grid control scenario (right).

Assessing the potential of power-to-heat SGC for overproduction limitation in power system requires embed in quasi-real boundaries condition. All system components used to create system reflecting system idea are detailed with appropriate mathematical models expressed by differential and algebraic equation simulated in TRNSYS software [9]. Prepared simulation layout is shown on Fig. 5.

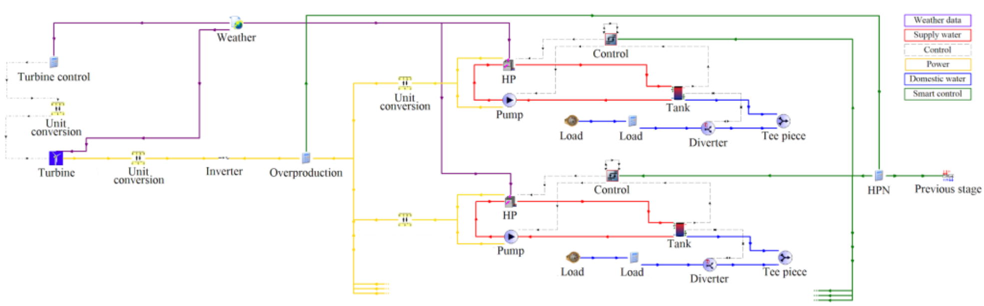

Fig. 5. TRNSYS simulation model.

The production (power supply) site was represented by the Type90 model parameterized with the Nordex N27/150 wind turbine power curve and required technical data [10]. The demand (power consumption) site consist of the individual HP units (Type917) with the thermal energy storage (Type4) for the domestic hot water (Type14) with ASHRAE profile [11]. The temperature of tap water is stabilising independent on time by mixing in Type11 with cold water to ASHRAE requirements [11]. Type2 model reflecting the control system delivered by the HP manufacturer with the default setpoint (DSP) temperature. The weather data came from the Poland database for Kołobrzeg city. TRNSYS flexible model was built to allow using technical and climatic data specific for other locations and systems in further research. Despite the established power source and meteorological condition, the conclusions will be proper to other renewable power sources or them groups.

In simulated systems the overproduction is monitored with very short time-step (5 seconds) in annual scope. For annual assessment the four groups of simulation output data were collected: renewable and conventional power consumptions, power system overproduction and individual HP demand site condition (temperatures and operation mode).

SGC strategy involves individual HP to shaving the overproduction peaks. While the system is balanced, the HP units operate in DSP mode (45°C) Every HP unit will automatically switch on and off keeping DSP by the basic manufacturer's controller according specific profile of domestic hot water consumption. In the case of excess power (overproduction), the SGC will switch the appropriate number of HP groups to overheating setpoint (OSP) temperature 70°C for power-to-heat store mode. The aim is to achieve power system balance by active SGC of HP power consumption, according to the current electricity overproduction. Specific groups of HP units will operate as long as the overproduction exist. The overproduction was limited by the amount of controlled and ready to OSP work HP units.

3 Preliminary results

The dynamic mathematical model of investigated power system, build in TRNSYS software, includes and simulates all devices, controls, operation modes and energy flows. The whole year simulation results enable interpretation and assessment both the input and output data. To illustrate the acting and potential of SGC strategy the four most characteristic operation patterns in power system are shown. Each pattern includes three sections illustrating the HP operation, generated power variability and water temperatures in storage tanks. The top section shows the operation modes of five HP groups. Particular HP group is characterised by three operating modes: OFF (switched off), DSP (operation in default domestic hot water setpoint) and OSP (operation in overheating domestic hot water setpoint). The middle section shows the generated wind power and power overproduction in the system. Dashed line represents the minimum overproduction power to activate SDC strategy. The bottom section presents the hot water temperature changes. Temperature in storage tank increases by HP charging and decreases by domestic hot water consumption.

The pattern on Fig. 6 illustrates the operation mode of five HP groups in case of negligible overproduction in power system. In well balanced power system SGC sets the DSP in all HP units. Almost all generated power is consumed, which indicates the high system efficiency in relation to the electricity unit. While overproduction is lower than the minimum OSP switch level in SGC strategy (dashed line), the SGC did not interfere with the HP control. This pattern defines the base operation mode to assess the SGC effect and actions in the following cases.

The second pattern (Fig. 7) illustrates the long-term and large overproduction case in power system. In green overproduced, unbalanced system the SGC automatically sequentially switches HP groups into OSP, to consume and store increased excess power. Finally, all controlled HP units operate in OSP mode and all domestic hot water tanks will be fully load. This case illustrates availability of fast-respond SGC strategy to power system balancing support by active short-term electricity consumption increase in controlled HP. The SGC stores the excess green energy in overheated tanks to utilise during green power deficits.

Fig. 8 illustrates the full potential of SGC strategy in dynamic conditions. Two specific periods in energy supply and demand are visible: green power overproduction period and green power deficit period. Excess power forces the SGC to OSP sequentially switch and HP fully thermal energy storage. The accumulated heat will be consumed in green energy deficit period with no conventional power demand. Two advantages of SGC strategy are noticeable: the reduction of overproduction problem and no conventional power demand for almost one day.

The SGC achieves beneficial results both in energy and environment approach. The SGC covering overproduction could also cause in electricity price reduction and minimise battery power accumulation with higher environmental and economical costs.

In real conditions the excess green power periods can occur frequently, more than once a day. The fourth pattern (Fig. 9) includes more than one period of overproduction with too short interval among causes non-fully thermal energy utilisation. First overproduction forces the SGC to OSP switch. The surplus green power storages in overheated domestic hot water tanks will not be fully consumed in the DST mode. During the second overproduction period SGC switches HP into OST, although the tanks low discharged-levels enables power utilisation. This issue is connected with mismatched amount of connected HP to SGC and overproduction peak size. To fully load the potential the SGC strategy should be implemented on area with large number of smart grid consumers.

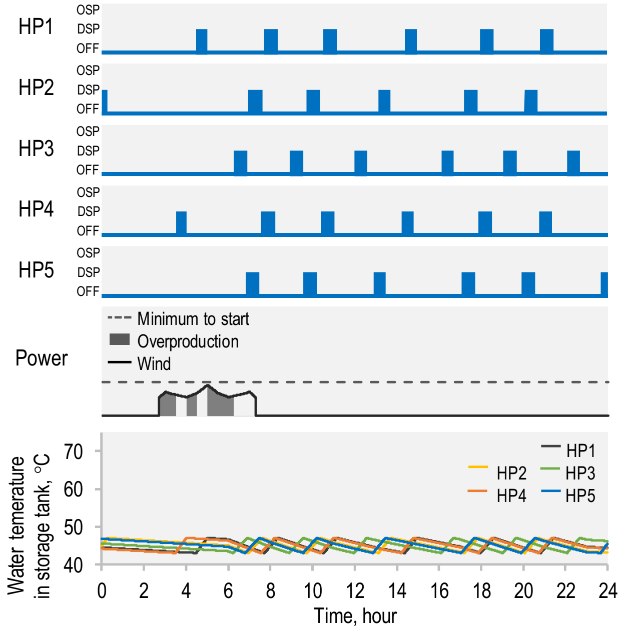

Fig. 6. Smart grid control in default setpoints conditions.

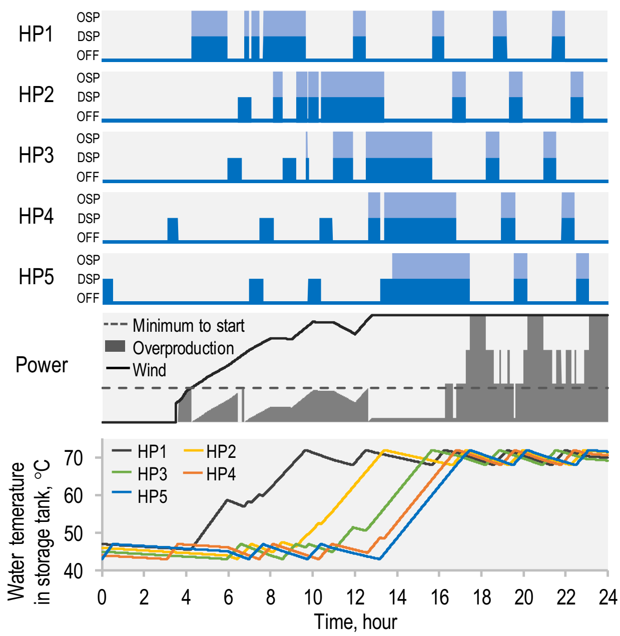

Fig. 7. Smart grid control in case of long-term overproduction.

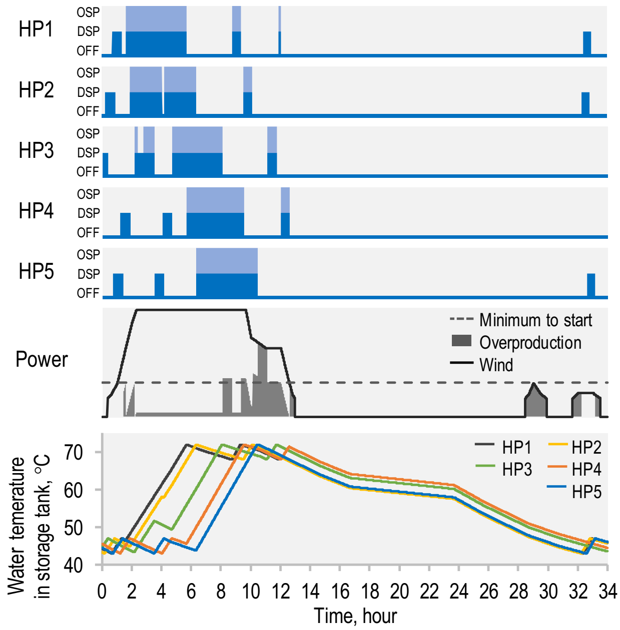

Fig. 8. Smart grid control in case of short-term overproduction and fully thermal energy utilisation.

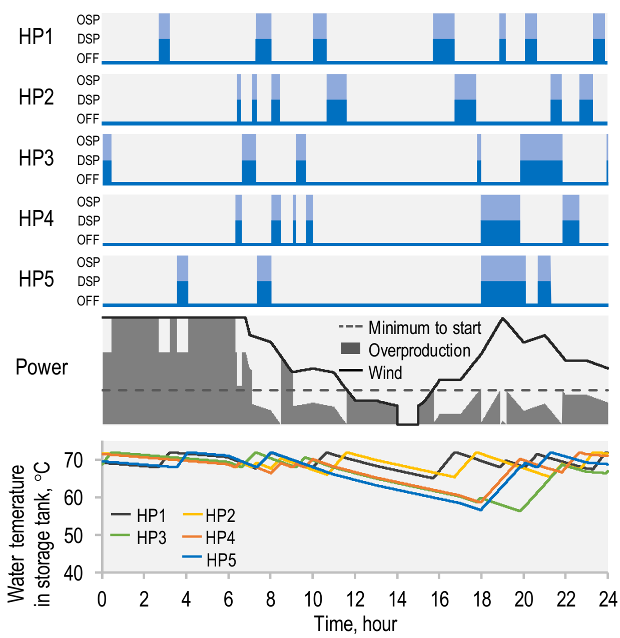

Fig. 9. Smart grid control in case of multiple overproduction day.

4 Conclusions

Ever-increasing renewable power sources caused by legislation and environmental impact limitation, generates pros and cons on power market level. Unbalance and power system blackouts caused by green power overproduction will be the major challenges of going more and more renewable. Nowadays, technology development aim is to extend and overwrite control procedures to overproduction minimisation. Purposed Smart Grid Control (SGC) is investment and environmental favourable. The SGC strategy is based on existing generation, transmission and demand infrastructure. Applying flexible and fast-respond tool for active balancing power system with large scale of renewables, will be achieved by using individual heat pumps with thermal energy storage. Using SGC strategy to green power overproduction limitation creates double-environmentally friendly system. Firstly, by using renewable power to supply HP units as a renewable heat sources, secondly by utilising excess green power to overheating and using accumulated thermal energy while lack of green power. SGC on the global level could: mitigate environmental impact of energy generation through them more fully usage, on country level increase the power production efficiency and ensure energy security, and on user level reduce HP operating costs.

Dynamic mathematical models enabled to simulate and tracking the operation modes and energy flows in whole year period. Based on simulation results it can be seen that investigated strategy caused beneficial both by fully and partly overproduction utilisation and is promising solution to balance power system with cheap and easy to implement smart grid strategy. The potential of implementation in all countries are large enough to further develop this control strategy. In this paper SCD was based on domestic hot water storage but could be also extend on HP space heating by active using the buildings thermal capacity. Proposed solution uses modern technologies and supports development of green power sector moving them into a low-carbon future.

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