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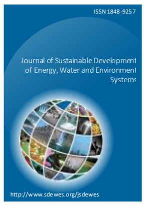

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Decarbonised District Heat, Electricity and Synthetic Renewable Gas in Wind- and Solar-Based District Energy Systems

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ABSTRACT

Low availability of sustainable biomass prevents transition of district heating in Europe away from fossil fuels. The need for sustainable fuels stems from current energy generation structure, which mainly relies on centralised combined heat and power operated as baseload units. Our study shows that districts with generation of renewable power, heat and synthetic natural gas can reach complete energy system decarbonisation even without biomass, only using wind and solar power as primary energy. It requires rethinking of interactions between electricity, gas and heating networks and a polygeneration solution with power-to-heat and power-to-gas technologies to fully utilise local solar and wind power and cover peak demands. Power-to-heat as baseload units supported with power-to-gas for seasonal and back-up energy storage are proposed as novel district heating approach. The operation of such polygeneration is tested successfully using a model of a Finnish district. Carbon dioxide circulation is analysed together with capacity requirements to synthetic natural gas and needed wind power installation. Resulting complete decarbonisation requires coordination and flexible operation of power-to-heat and power-to-gas capacity together with gas-fired combined heat and power plants and heat-only boilers, which ensures that renewable power production, heating and power needs, security of supply and grid limitations are met.

KEYWORDS

Renewable energy, Decarbonisation, District heating, Sector coupling, Polygeneration, Power-to-gas, Power-to-heat, Synthetic gas.

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INTRODUCTION

Today, large District Heating (DH) systems are often well-established co-/poly-generation systems that generally consists of conventional centralized Combined Heat and Power (CHP) units, used as baseload units, and Heat-Only Boilers (HOB) for peak heating needs [1]. For some regions with good biomass availability, e.g., Baltic and Nordic countries, such energy systems are often based on biomass fuels. Biomass accounts for about 90% of renewable heating in Europe [2]. In general, European DH and cooling systems are still mainly based on utilization of fossil fuels such as coal (15%), natural gas (46%), and oil (10%) [2], often because of limited availability of local, sustainable and affordable biomass fuels [3]. Many towns and cities in Europe have such efficient but fossil-based polygeneration systems in place, and face large challenges with their future deep decarbonisation targets, e.g., fossil-free energy production in 2030-2050 [4]. This opens up interest for Power-to-Heat (P2H) and Power-to-Gas (P2G) DH solutions based on renewable power. Our study investigates possibilities of the foregoing technologies in decarbonisation of a local energy system.

Similarly to power generation, replacement of fossil-fuelled power plants with variable wind and Photovoltaic (PV) solar power production leads to challenges in balancing the production fluctuations on different time scales [5, 6]. Storage or other sources of flexibility are needed to avoid curtailment during periods of high intermittent generation and ensure generation adequacy [7]. For reliable DH generation in urban areas situated in colder climates, this challenge could be even more pronounced because of the limited availability of solar power [8] and risk of low wind production coinciding the times of peak heating demands in wintertime. Our study quantifies this specific problem and estimates the possibilities to carbon neutral district energy system in Nordic latitudes.

P2H technology is needed to convert renewable power into district heat. Large-scale Heat Pumps (HP) are already commonly used in DH production in Scandinavia, especially Sweden [9]. HPs can start up and be turned off quickly, which makes them a convenient source of flexibility [10]. The utilization of large-scale HPs have increased due to relatively low electricity prices, requirements for renewable heat production, technology development and successful investments [11]. According to analysis of Pieper *et al.* [12], specific investment costs of HPs generally decrease with increase in the capacity. Due to high investment costs, P2H plants are not used to cover peak loads [1]. Except for some pioneering installations, e.g., ground source HPs in Olot [13] and datacenter waste heat recovery by HP system in Mäntsälä [14], the centralized P2H plant have not been used as the main source for district heat production, but the available large-scale installations supplement the heat source arsenal of the DH systems of cities. Our study shows that the idea of utilizing HP as a baseload source of heat can be justified.

Hydrogen has been long studied as an energy carrier and a storage solution [15]. Water Electrolysis (WE) systems can convert renewable power and water into renewable hydrogen (H_2) and oxygen (O_2), while conversion losses are mainly waste heat. According to Bohn and Lindner [16], utilisation of waste heat can increase total efficiency of electrolysis by 15%. Cost and technical characteristics of WE technologies as well as future trends are presented in reviews [17-19], all indicating that attractive investment costs and performance are within reach before 2030. For a 6 MW_{el}, WE demonstration facility [20] show that H_2 production costs are strongly dependent on use-case and annual Full Load Hours (FLH), anticipating that high FLH are needed for WE and P2G to have a chance to reach an economy of interest.

For urban energy systems with its power and heating sectors, the impact of fossil Natural Gas (NG) blended with renewable H_2 from WE is studied in Nastasi and Lo Basso [21], emphasizing requirements of older building stock to supply of heat at higher temperatures that can be generated by CHP and HOB units using such hybrid fuels. Still, the maximum H_2 content in an operative NG grid is restricted to a few percent by volume by widely varying national limits that depend on the grid operator and connected customer devices [22], which imposes strong limitations on direct H_2 feed at least into the networks connected to national or international gas grid [23]. The case study in Simonis and Newborough [24] shows that for such limiting circumstances, direct H_2 feed provides only a very small decarbonisation potential for the needed local gas consumption. In addition, H_2 storage especially in liquid form which requires substantially less space is expensive and inconvenient and, therefore, other chemicals, e.g., ammonia [25] and methanol [26], which serve as H_2 carriers have been considered.

P2G, the conversion of renewable power via H_2 and methanation (i.e., hydrogenation) of carbon dioxide (CO_2) into Synthetic fossil-free methane (SNG), has received attention in recent years [5], with recognition of key role of fossil-free CO_2 [27] besides the renewable H_2. Renewable energy integration with energy storage to SNG has been found to have significant potential at different regions of Europe. For example, in Northern Germany, wind power storage by biogas upgrading process was estimated to enable storing up to 1.5 TWh of electricity annually as renewable gas [28]. In Berlin-Brandenburg region, the methanation technology together with gas storage to complement bioenergy, wind and PV production was seen as a pathway to high-level renewable energy contribution [29]. In UK, use of NG network different energy carriers was found to significantly contribute to network's CO_2 emissions [30]. In addition, the interactions of P2G with the gas, electricity, heat and/or CO_2 markets have been found to partially transfer capacity and flexibility problems from the electricity to the gas sector [31] and as a long-term energy storage to reduce Levelized Cost of Energy (LCOE) of the energy system [32]. P2G has the advantage of existing infrastructure for methane transport, storage, and utilization, compared to H_2 which requires new challenging infrastructure [33]. Still, P2G suffers from additional energy losses compared to WE, which, however, can be recovered as waste heat for, e.g., DH purposes. A proper DH-integration could therefore enhance P2G as well as P2H efficiency, but to the authors' knowledge, no such integration study has yet been presented.

Integration of Renewable Energy Sources (RES) into CHP-based DH systems exploiting thermal heat storages has been widely modelled [32, 34-37]. It has been found that the optimal operation of thermal heat storages depends on the heat demand and power price [34]. Also, heat storages has been considered for biomass-fired CHP system and it has been found that optimal configuration is different depending on whether economics or energetic aspects are considered more important [35]. In addition, balancing large amounts of wind power with heat storages in the energy systems, where CHP provides flexibility to power production has been analysed [36]. In DH network fed by CHP or HOB, load allocation between the plants has been optimized to enable more accurate operation of the network [38].

Less attention has been paid on HP utilisation in RES integration to DH. According to review made by Bloess *et al*. [39], the most of the modelling approaches related to HP utilisation for renewable energy integration concentrate on cost minimisation. Our study focuses more on renewable power integration to maximize decarbonisation and efficient gas utilisation. In two of the studies concentrating on flexibility maximisation and dispatch simulation, the HP solution involved a set of hundred domestic HPs [40] or space heating and domestic hot water HPs [41] instead of a centralized HP solution for DH as in our study. Although, large amount of small-scale HPs has been shown to enable integrating significant amount of wind energy to heating, resulting in system-wide emission reduction when fossil fuel burning heating equipment is replaced with HPs [41], such decentralized solution has been found to cause difficulties in harvesting of especially downward load modulation [40].

Models of centralized HP solutions for renewable electricity integration to DH are rare. In Østergaard and Andersen [42], centralized HPs are used in modelling approach, but their operation is optimized against spot market, instead of evaluating the potential for energy system decarbonisation, as done in our study. In Salpakari *et al*. [43], P2H conversion was used in load shifting for wind and PV in Helsinki. They suggested that 80% of the energy of the needed DH could be covered by a centralized HP solution, up to 90% if supporting electric boilers were used, but did not account for the performance decrease of the HP during peak heating times that need higher DH supply temperatures. Also, during peak heating times, the proposed solution relied strongly on the heating power from conventional HOB and CHP assets, that were assumed to use conventional fossil fuels like natural gas. The study found also that loss of CHP production from existing plants made P2H configurations less profitable, but it was indicated that replacing some of the CHP plants with variable renewable energy and P2H should be studied. Our study evaluates the new technical solutions for renewable energy integration regardless of the existing system merit order, which opens up the discussion of whether the original merit order should be respected at all if the goal is full decarbonisation.

In our study, the energy system on a district level and interactions between power, gas and DH grids in European subarctic climate regions are analysed in order to evaluate the future medium-scale DH and polygeneration system in terms of capacities, utilization rates and emissions. A detailed simulation model of a district from the Finnish town of Suonenjoki is used to illustrate the energy system operation at medium-scale DH network level and possibilities of conversion assets, namely P2H and P2G. The energy consumption, building stock and DH grid part of the model has been earlier presented in Paiho *et al.* [44] in the context of assessing energy-efficient refurbishment of buildings at district scale. This validated model integrates building and DH network simulation, and was extended in our study for the H2020-project PLANET with a polygeneration model for district level P2H, P2G, CHP and HOB units. CO_2-circulation and renewable Synthetic Natural Gas (SNG) production and storage needs of this novel polygeneration system are analysed. The results show, how such a district with a novel polygeneration solution consisting of renewable power, heat and fuel gas generation can reach a complete energy system decarbonisation, without the utilization of biomass.

METHODS

The district energy system and interactions between power, gas and DH grids in European subarctic climate regions are analysed using a polygeneration model. The parts of the model describing conventional DH and power production, interactions between power, gas and heat, potential of renewable energy sources as well as simplified merit orders used to operate polygeneration systems are described in the following.

Polygeneration model

The energy system of the modelled district is schematically presented in Figure 1. It consists of energy demand and DH network model as well as a polygeneration plant model connected to external electricity and gas supply networks. In our study, the focus is on the polygeneration model and related generation scenarios for decarbonisation.

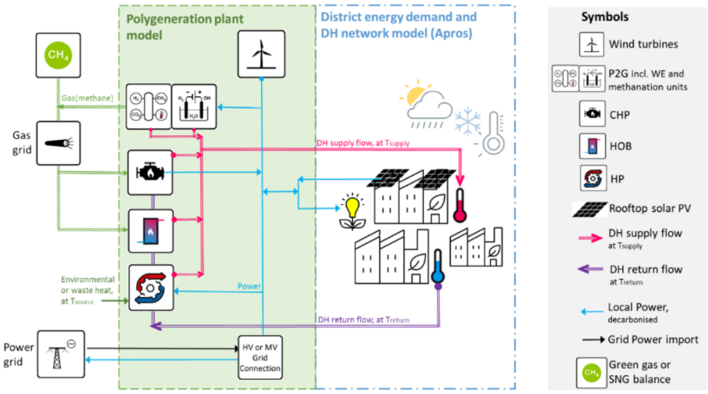

Figure 1. Modelled district energy system

In districts with small to medium-size DH networks, generation is often concentrated to one or two locations only. For our study, and for the use of H2020 project PLANET [45], a single-point polygeneration model was created, describing a local polygeneration plant with P2H, P2G, CHP and HOB units connected to the local DH and power grids, and having at least a feeding line from the gas grid.

District heat and power demand

The energy demand feeding the polygeneration model can be covered by power and DH measurements directly, if available. Such measurements must have good enough granularity, being at least hourly measurements. Besides district's aggregated active power consumption, a minimum measurement set must contain required DH supply temperature ($T_{\text{DH,supply}}$) and mass flow ($\dot{m}_{\text{DH}}$) from the plant to the DH network and its heat consumers, and the resulting DH return temperature ($T_{\text{DH,return}}$) to the plant. Using the heat capacity of water (c_p), such measurement set provides for a small to medium DH network the momentary DH consumption ($Q_{\text{cons,DH}}$) as follows:

$$Q_{\text{cons,DH}} = c_p \times \dot{m}_{\text{DH}} \, (T_{\text{DH,supply}} - T_{\text{DH,return}}) \tag{1}$$

Alternatively, a detailed enough model of the buildings' energy consumption behaviour, the DH network dynamics and power consumption can be used. In our study, a high fidelity thermal-hydraulic model of the districts buildings and DH network, which is presented briefly in Paiho *et al*. [44], was used to calculate the time and weather dependent power and heat demands as well as resulting DH supply and return temperatures and mass flows at the DH plant.

Conventional District Heating and power production

Gas-fired conventional DH production assets are not restricted to only use fossil natural gas, but can also be fired with renewable gas, i.e., biomethane from biogas or SNG. They could therefore be valuable assets in a decarbonized future, and are included in this decarbonisation analysis.

Gas-fired Heat-Only Boilers. The thermal efficiency of a condensing gas-fired HOB, including the dependency of flue gas recovery efficiency on the incoming DH-return temperature, was modelled using theoretical curves from Kuck [46] and Che *et al*. [47] for an excess air coefficient α = 1.05 typical for standard boilers. A linear relationship was fitted to the non-condensing temperature regime and a 3$^{\text{rd}}$ degree polynomial on the condensing regime of the flue gas recovery unit (c.f. Figure 2).

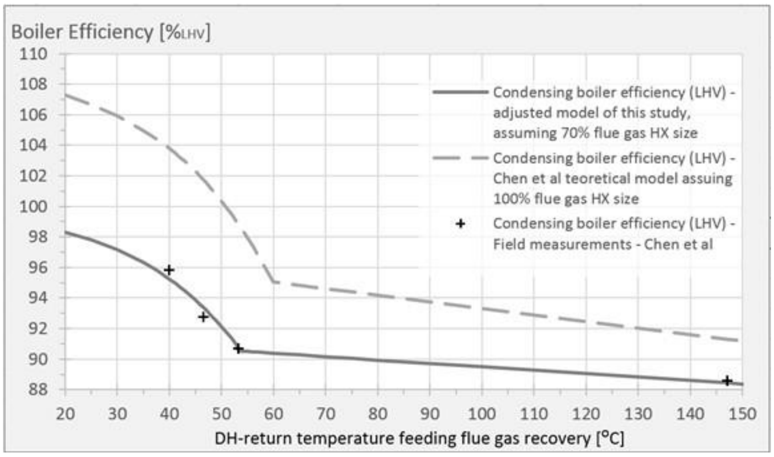

Figure 2. The effect of DH return temperature on boiler efficiency

A limit on the size of heat exchanger for flue gas heat recovery was added. Here a limitation of 70% of the theoretical maximum potential was used to fit the theoretical curve to the field measurement data of a 2.1 MW gas-fired HOB presented in Che *et al.* [47].

Gas-fired Combined Heat and Power units. The thermal efficiency of a CHP was modelled in a similar way as for HOB. In addition, for a requested heat output (Q_{CHP}), the resulting power output (P_{CHP}) was modelled using the P2H ratio (r_{CHP}) [48] of the CHP, which for conventional CHP units is assumed constant:

$$P_{\mathrm{CHP}} = r_{\mathrm{CHP}} \times Q_{\mathrm{CHP}} \tag{2}$$

In the scenarios where P2G was present, the plant was equipped with post-combustion carbon capture with capture efficiency of 85% [49].

Power-to-Heat

P2H unit considered in our study was a high-performance HP, supplying the heat to DH network.

District Heating level Heat Pump. A HP providing heat at temperature levels higher than a certain threshold, e.g., 70 °C to a DH network or an industrial process, can be considered a high-performance HP. The Coefficient of Performance (COP, i.e., ratio of useful heat output Q_{HP} to power input $P_{cons,HP}$) of the HP is modelled using the following equation:

$$\mathrm{COP_{DH}} = \frac{Q_{\mathrm{HP}}}{P_{\mathrm{cons.HP}}} = \eta \times \frac{T_{\mathrm{SINK}}}{T_{\mathrm{SINK}} - T_{\mathrm{SOURCE}}} \tag{3}$$

where T_{SINK} and T_{SOURCE} are the absolute temperatures (K) of heat exchanger on the hot side (sink) and cold side (source), respectively. η is a dimensionless degradation factor, describing process imperfections compared to ideal Carnot cycle. In Arpagaus *et al.* [50], a market overview of commercially available high-temperature HPs reports COP-values which on average correspond to η = 0.6 (range between 0.4 and 0.7, depending on HP design) for an operation environment with T_{SINK} of 363.15 K (90 °C) and T_{SOURCE} 293.15 K (20 °C) or lower. A value of η = 0.7 corresponds to some HP designs using environmentally friendly CO_2-based refrigerant, this HP was reported to have a capacity to reach T_{SINK} of 383.15 K (110 °C). As a conservative estimate for our model, η = 0.6 was used for a modern high-performance HP [51]. For T_{SINK}, the momentary value of the DH supply temperature was used, while T_{SOURCE} depends on the available waste or environmental heat source.

The resulting values of HP COP for selected temperature ranges of HP source and DH supply are shown in Figure 3.

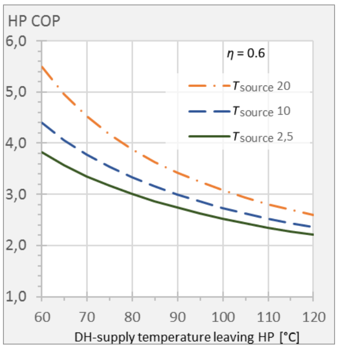

Figure 3. The effect of HP source and DH supply temperatures on COP

Power-to-Gas

A P2G unit producing SNG consists of at least a water electrolyser, and a subsequent methanation unit. Optionally, if local utilization is possible, such a configuration can also produce useful waste heat and oxygen.

Polymer Electrolyte Membrane Water Electrolysis (PEM-WE). The PEM-WE technology has experienced an increased preference in P2G applications [52]. It has a fast response, in the order of seconds and is thus able to provide grid management services, such as, e.g., load following and peak shaving [53], and was selected as technology for our study. Because of fast response time (compared to simulation time step of one hour), the PEM-WE unit could be straight-forward modelled to produce H_2 from local excess power with a simple conversion efficiency of 70% Higher Heating Value (HHV) [24]. Part of the energy lost in this conversion can be recovered as waste heat. In our study, a recovery factor of 0.5 was assumed for the PEM energy loss.

Methanation. In a decentralized employment supporting distributed power generation, the methanation process unit must also be responsive and suitable for load-following operation. Biological methanation has a far better load-following capability than chemical (catalytic) methanation, and laboratory tests have shown that immediate load changes from 100% to 0% and several weeks long rest periods can be achieved [54]. Also, in contrast to chemical methanation, biological methanation is tolerant to several gas impurities such as hydrogen sulphide (H_2S) and ammonia (NH_3), and is easier to handle with low operating temperatures (40-70 °C) [55]. Consequently, biological methanation was selected for our study. Because of the load-following capability, the methanation unit could be modelled using a simple thermodynamic conversion efficiency of 78%. The energy lost in this conversion can efficiently be recovered as waste heat. In our study, a recovery factor of 0.9 was assumed for the methanation energy loss.

Solar and wind power

Generation of local renewable energy using rooftop PV panels and a wind turbine, was considered as alternative electricity sources for the polygeneration model of the district.

Local on-shore wind power. For the location of the district, local wind power potential can be calculated using the Virtual Wind Farm model [56], which is part of renewables.ninja project [57].

Merit orders and power grid limitations

Heat and electricity generation installations are usually operated in a certain order determined by operation costs. Selected orders assumed in our study are described below.

Conventional merit order for District Heating production. In small and medium-size DH networks, the conventional merit order is to operate the CHP as baseload unit and use the HOB as peak unit [58]. If cheap or free waste heat is available, such as P2G waste heat, this heat is usually utilized first, before using the CHP. In our study, if a HP is available within imposed power grid import limitations, it is used as intermediate unit on top of the CHP before the HOB is started. This kind of a conventional straightforward merit order, which results from the normally low net heat production cost [59] and high investment cost of the CHP, is referred to as 'CHP first' merit order in our study.

Power-to-Heat merit order for District Heating production. In contrary to the 'CHP first' merit order, the HP is used as a baseload unit within imposed power grid import limitations, CHP as intermediate unit, and HOB as peak unit. If P2G waste heat is available, this heat is utilized first, before using the HP. This novel kind of a merit order is referred to as 'HP first' merit order in our study.

Power production merit order and grid limitations. The merit order of the DH production determines the power production of CHP plant. Together with the local solar PV and wind power production, the power produced by CHP can locally be utilized to cover baseload and P2H consumption, whenever possible. In case of remaining excess local renewable power exceeding a selected threshold, the P2G unit is started in the polygeneration model. In case of remaining excess power despite P2G operation at full capacity, this power was exported within the grid limits for reverse power flow, and remaining power exceeding the reverse flow limits was curtailed.

Targets

The objectives set for the district may be split into two categories: decarbonisation and self-sufficiency, and security of supply and avoided grid expansion.

Decarbonisation and self-sufficiency. For the district, the primary targets are to meet the DH and power demand and to decarbonise this demand as completely as possible. Our study assumes that there is no net CO_2-import via the (national) power grid on annual base, if the district exports on annual base more renewable power to the power grid than it imports, regardless of the CO_2-emission levels of the power grid. Therefore, to support the decarbonisation target, one primary target for the district is also to reach, in terms of electrical energy, zero import or net export to the power grid. To achieve this, local renewable power generation (wind) power capacity is increased until zero import or net export of power is reached. For scenarios with a P2G unit, the self-sufficiency target can be to attain a level of SNG fuel production that entirely covers the local fuel needs for the operation of CHP and HOB.

Security of supply and avoided grid expansion. During extended periods with very low outdoor temperatures, there will be a peak period in DH energy consumption. At the same time, there may be a considerable risk for non-existent solar and wind power production. The local DH and power production must meet such challenging peak heating periods without exceeding import limits of the power grid.

CASE DISTRICT WITH MEDIUM-SIZE DISTRICT HEATING NETWORK

To illustrate the operation of a mid-scale DH network level and its future P2H and P2G options in cold climate conditions, the central district from the small town of Suonenjoki, located in the middle of Finland (62° 37' 30" N, 27° 07' 20" E), was selected for detailed study.

Description of the case district

Figure 4 presents the buildings and local DH network in the centre of Suonenjoki.

The approximately 100 buildings in the area had a total floor area of ca. 116,000 m^2. Buildings represent several types: mainly residential but also school, hospital, office and other public and industrial buildings. Major part of the building stock was built between 1960 and 1980. Most of the buildings are connected to the DH network but there are also other types of heating systems, such as direct electrical heating.

The total annual energy use in buildings amounts to approximately 16.7 GWh of district heat and 9.1 GWh of electricity. The climate conditions are characterized with average outdoor temperature 4.2 °C with summer high of 27.4 °C and winter low −31.8 °C. The potential of solar PV production is ca. 810 kWh/kW$_p$.

Figure 4. Schematic diagram of Suonenjoki DH network and building stock

District's power and heat consumption

DH and power consumptions are dependent on both heating needs and user-patterns. To estimate these consumptions, a validated physical simulation model of the example district was used [44]. This detailed model includes residential power and domestic hot water consumption patterns, electric heating, building rooftop-PV, thermal mass and heat demands of buildings, temperature levels at buildings' heating substations, as well as pressures, mass flows, supply and return temperatures in pipes of the DH network.

One-year simulation runs with the weather conditions of 2016 were performed in order to obtain simulation data with hourly resolution, from which resulting DH and power consumptions (displayed in Figure 5) as well as DH supply and resulting return temperatures of the DH grid (Figure 6), which were used in our study.

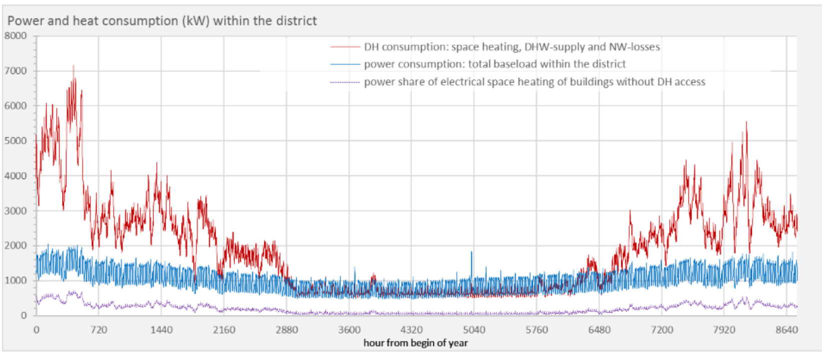

Figure 5. Simulated DH and power consumption in Suonenjoki district

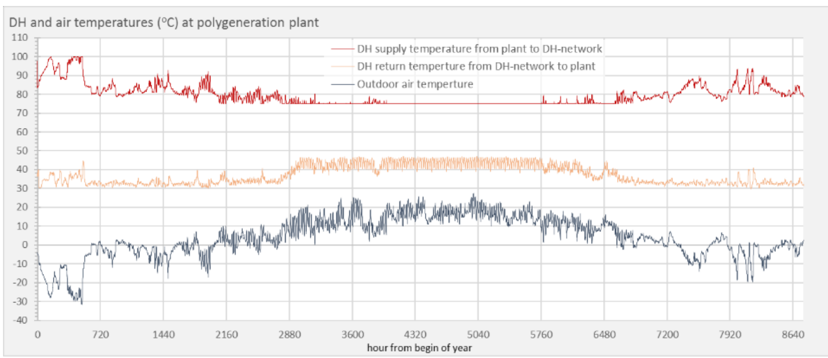

Figure 6. DH supply and return temperatures in Suonenjoki district

Security of supply. From Figure 5 and Figure 7, it can be seen that there is a peak period in DH energy consumption in the beginning of the year (approximately 1.5 week long period with very low outdoor temperature), while at the same time almost no wind nor solar power is produced. The DH and power production must meet this challenging peak heating period so that the import limits of the power grid are not exceeded.

District's polygeneration scenarios

A baseline scenario 'Baseline' describing the starting point scenario with current conventional CHP and HOB assets was created, solely based on gas-fired DH-production. CHP production capacity was set to 2,500 kW DH/1,000 kW power, (at a P2H ratio set to be r_{CHP} = 0.4, typical for systems with high heat demand) [48], to reach a typical high utilization over 5,000 FLH, while a HOB capacity of 4,660 kW was needed to completely cover the remaining peak demand. Power grid limits for import and reverse flow to and from the district were selected to be 3,000 kW, i.e., 50% higher than the estimated 2,000 kW power consumption peak for the district with conventional polygeneration system (c.f. Figure 5).

The first evolution scenario 'noP2H-CHP first' for decarbonizing the power use describes the introduction of local solar and wind power to reach a 100% self-sufficiency in power on yearly basis, without any P2H or P2G assets on the DH production side.

In the subsequent scenarios, the P2H and P2H + P2G related scenarios, a lake water-source HP was added with the same DH capacity as the CHP. The 'P2H only' scenarios have only the HP added, while the 'P2H + P2G' scenarios have a P2G unit with a capacity set to a level that delivers the needed SNG for the CHP and HOB operation. In case of remaining excess local renewable power exceeding a selected threshold of 200 kW, the P2G unit was started. The objectives of the scenarios are summarized in Table 1 below.

Table 1. Objectives of the scenarios

Scenario	Description			
	Self-sufficient in renewable electricity	Self-sufficient in renewable gas	DH de-carbonisation	HP runs before CHP
Baseline	No	No	No	No HP
noP2H-CHP first	100%	No	No	No HP
P2H only-CHP first	100%	No	Partial (11%)	No
P2H only-HP first	100%	No	Partial (84%)	Yes
P2H + P2G-CHP first	100%	100%	100%	No
P2H + P2G-HP first	100%	100%	100%	Yes

For the HP added in the scenarios, our study assumes lake water as heat source. For a large Finnish lake, we approximate T_{SOURCE} using a yearly sine wave characterized with a minimum of 2 °C (lake bottom temperature in wintertime) and a maximum of 12 °C (summertime, higher water layers). This approximation corresponds to the measured lake water temperatures of the Finnish large lake Kallavesi (located at 62° 45' N, 27° 47' E, and having a maximum depth of 75 m) at 40 m depth during wintertime and 15 m during summertime [60].

In the scenarios, the local wind power of the district was calculated with the Virtual Wind Farm model [56]. For this calculation, the library model of the 'Vestas V90' turbine with a rated capacity of 2,000 kW was selected, and a hub height of 80 m was assumed. The resulting hourly time series was multiplied to the needed total wind power capacity of each scenario.

Local solar PV power was calculated using the physical simulation model [44] of the example district. In the example district, rooftop-PV was assumed to be installed on all roofs of public buildings (hospital, school, ice arena, swimming hall, etc.) having relatively good solar potential. Technically possible panel area was assumed to be 50% of this roof area. For panel azimuths and tilt angles, the available data on roof slopes were used with the exception of flat roofs, for which the assumptions made were south orientation and a slope angle of 40°, which gives optimal solar electricity production in [61]. No open-field installations were assumed. The resulting local solar PV production was calculated using hourly local irradiation measurements for 2016 and the building-integrated PV sub-models [62] of the physical simulation model [44] of the example district.

As example, the resulting curves of solar and wind power generation (kW) within the district are shown in Figure 7 for the full decarbonisation scenario 'P2H + P2G-HP first'.

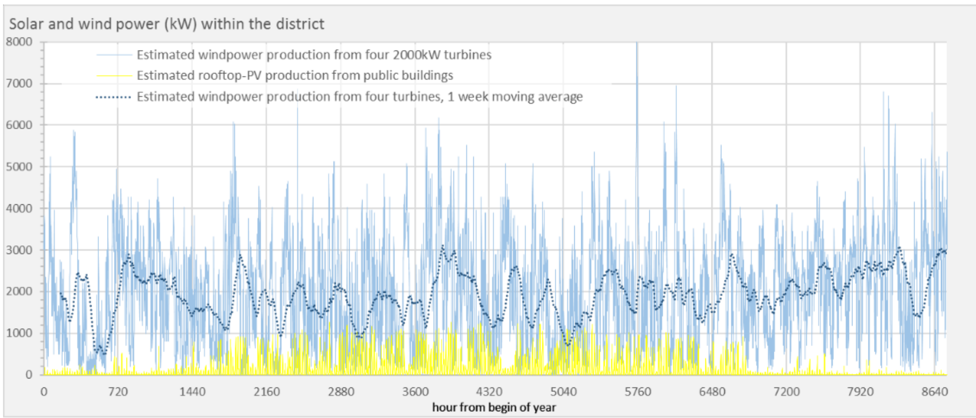

Figure 7. Estimated wind and solar power generation within the example district, scenario 'P2H + P2G-HP first'

RESULTS AND DISCUSSION

The calculation results for the scenarios described above and using the data of the year 2016 on weather and estimated renewable generation for the location of the example district are summarised in Table 2. Detailed duration curves for the district heat production are also displayed in Appendix 1.

Table 2. Results for calculation year 2016

	SI-unit	Baseline	noP2H	P2H only		P2H + P2G	
Merit order (= baseload unit)		CHP	CHP	CHP	HP	CHP	HP
HOB capacity (DH)	[kW]	4,660	4,660	2,160	2,160	2,160	2,160
CHP capacity (DH)	[kW]	2,500	2,500	2,500	2,500	2,500	2,500
HP capacity (DH)	[kW]	-	-	2,500	2,500	2,500	2,500
P2G capacity (power input)	[kW]	-	-	-	-	7,000	1,250
PV capacity (nom.)	[kW]	-	1,270	1,270	1,270	1,270	1,270
Wind power capacity (nom.)	[kW]	-	1,200	1,500	5,200	16,500	8,000
HOB FLH	[hours]	545	545	85	85	65	80
CHP FLH	[hours]	5,560	5,560	5,560	940	3,550	790
HP FLH	[hours]	-	-	940	5,560	540	5,005
P2G FLH	[hours]	-	-	-	-	3,780	4,960
PV FLH	[hours]	-	860	860	860	860	860
Wind FLH	[hours]	-	2,116	2,116	2,116	2,116	2,116
CHP power production	[MWh]	5,560	5,560	5,560	940	3,550	790
PV power production	[MWh]	-	1,090	1,090	1,090	1,090	1,090
Wind power production	[MWh]	-	2,540	3,170	11,000	34,910	16,930
Power consumption*	[MWh]	9,100	9,100	9,640	12,840	35,970	18,690
Power net export	[MWh]	−3,540	90	180	190	3,580	120
Wind power curtailment	[MWh]	-	0	0	10	120	60
NG or SNG consumption	[MWh]	23,060	23,060	20,590	3,640	13,140	3,080
SNG production	[MWh]	-	-	-	-	13,130	3,080
Flue-gas CO_2 emissions	[ton]	4,570	4,570	4,080	720	2,600	610
CO_2 captured for P2G	[ton]	-	-	-	-	−2,210	−520
CO_2 deficit for P2G (import)	[ton]	-	-	-	-	−390	−90
District's local CO_2 emissions	[ton]	4,570	4,570	4,080	720	0	0
CO_2 emissions from grid power**	[ton]	1,050	−30	−15	−56	−1,060	−35
Local CO_2 emission reduction	[%]	-	0	11	84	100	100
Total CO_2 emission reduction**	[%]	-	19	28	88	119	101

* Including P2H and P2G

** Assuming emission factor of 296 g CO_2/kWh for EU average electrical grid in 2016 [63]

Polygeneration and decarbonization results

The results obtained in the scenarios are briefly described below, and the impact on security of heat supply and needs for power grid expansion are discussed in the end of this section.

<u>The scenario for decarbonizing only the power use</u>. The scenario 'noP2H-CHP first' could reach with a modest 1,200 kW wind power installation a full decarbonisation of the district's power consumption, but not the DH consumption. The district's direct net CO_2-emissions would be 4,570 ton CO_2/year because of CHP and HOB operation for DH production. To reach a full decarbonisation, the needed fuel amount of 23,060 MWh must be bought as SNG or biomethane from outside the district.

<u>The scenario with Heat Pump and prioritised Combined Heat and Power</u>. The scenario 'P2H only-CHP first' could reach with a modest 1,500 kW wind power installation a full decarbonisation of the district's power consumption including the power needed by the HP, but only marginally decarbonised the DH consumption. The district's direct net CO_2-emissions would remain at the level of 4,080 ton CO_2/year, i.e., only a 20% reduction compared to the baseline, because of prioritized CHP operation for DH production. To reach a full decarbonisation, the needed external 20,590 MWh of renewable gas fuel must be bought as SNG or biomethane from outside the district.

<u>The scenario with prioritized Heat Pump and Combined Heat and Power</u>. The scenario 'P2H only-HP first' needed a 5,200 kW wind power installation to reach a full decarbonisation of the district's power consumption including the power needed by the HP, and decarbonized the DH consumption by 84%. The districts direct net CO_2-emissions would drop to 720 ton CO_2/year, because of prioritized HP operation for DH production, and to reach a full decarbonisation the needed external fuel amount dropped to 3,640 MWh of renewable gas.

<u>The scenario with Heat Pump, Power-to-Gas and prioritised Combined Heat and Power</u>. The scenario 'P2H + P2G-CHP first' needed a large 16,500 kW wind power installation, combined with a large 7,000 kW (in terms of electrolyser power input) P2G installation, to reach a full decarbonisation of the both district's power and DH consumption including the power needed by the HP and P2G unit. Approximately 2,600 ton CO_2/year would be used by the P2G unit, corresponding to all CO_2 of the polygeneration system's flue gas, i.e., enabling a full CO_2-reuse. However, because post-combustion carbon capture is estimated to have a capture efficiency of 85%, 390 ton flue gas CO_2/year would be lost into the air and must be obtained from other CO_2-sources, e.g., Direct Air Capture (DAC) or imported from outside the district.

<u>The scenario with prioritized Heat Pump, Power-to-Gas and Combined Heat and Power</u>. The scenario 'P2H + P2G-HP first' needed only an 8,000 kW wind power capacity, i.e., less than half compared to previous 'P2H + P2H-CHP first' scenario due to the prioritized HP operation. The full decarbonisation of the district's power and DH production is still reached with P2H and P2G. The needed P2G capacity would, anyhow, be dramatically reduced to 1,250 kW, which is only one fifth of the previous scenario, due to increased HP heat production. The reduction in P2G capacity reduces needed investment considerably. Approximately 610 tons of CO_2/year would be used by the P2G unit, and a full CO_2-reuse would be enabled. Only 90 tons of flue gas CO_2/year would be lost into the air and must be obtained from other CO_2-sources. The resulting DH and electricity production, electricity consumption and exchange with external electrical network for this scenario are presented on Figure 8.

Figure 8a-b depicts the utilization of different generation types in DH and power production. Baseload-type utilisation of HP can be clearly seen, while the P2G plant continuously operates throughout the year with high utilisation but in an intermittent mode with many start-ups and shut-downs, capturing the wind power intermittency. CHP plant is utilised only during rather rare periods of peak heat consumption, with less

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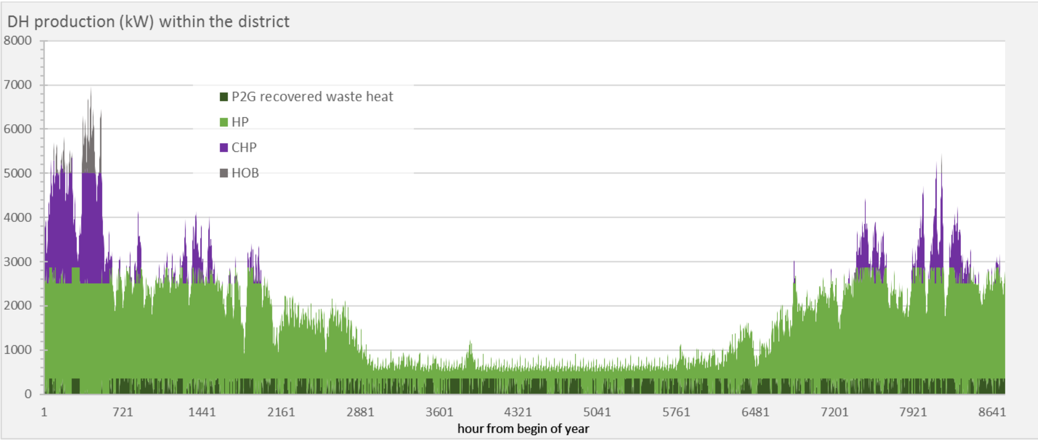
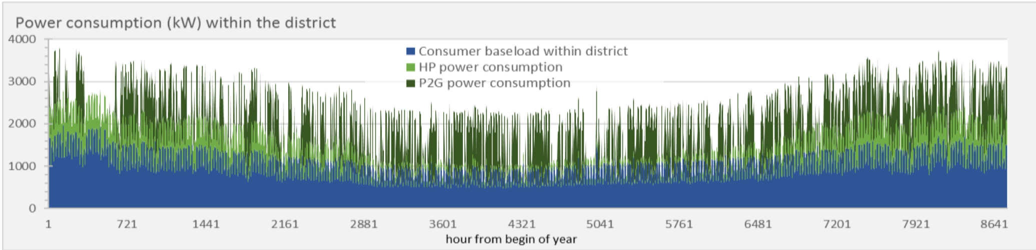
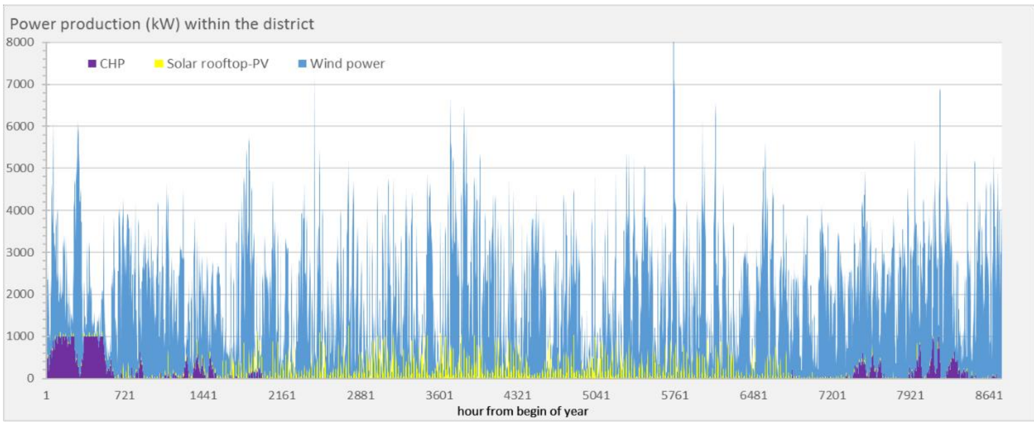
than 10 start-ups of the CHP during the year. HOB is only activated during the coldest weeks.



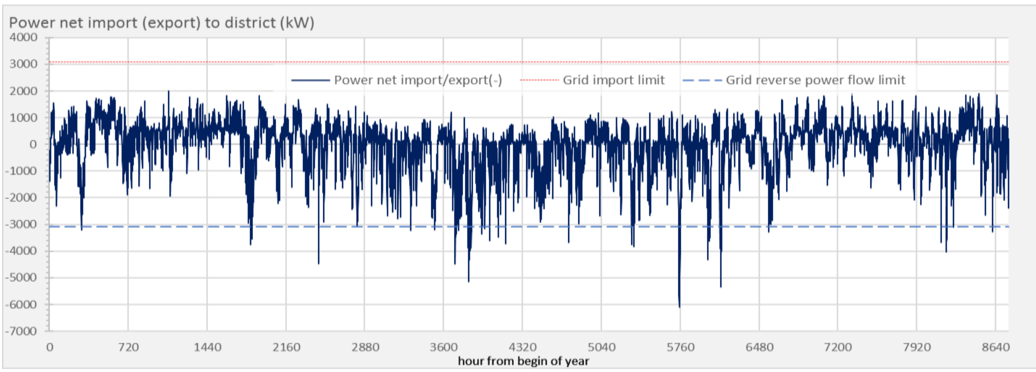
(a)



(b)



(c)



(d)

Figure 8. DH production (a); power consumption (b); power production (c) and net grid exchange for the 'P2H + P2G-HP first' scenario, enabling 100% decarbonisation (d)

Security of supply and avoided grid expansion. For all scenarios, the needed DH could be supplied to the customers, even during the coldest winter week without wind and solar power production, as shown for the 'P2H + P2G, HP first' scenario in Figure 8. At the same time, the estimated current power grid limitations could be met for both power export and import. This target was met despite the quite large wind power installations in the scenarios with P2G units, where 2.7-5.5 times larger wind power installation compared to the grid reverse power limit could be handled or absorbed within the district itself.

Sensitivity analysis of complete decarbonisation scenario

In complete decarbonisation scenario, the CHP plant is not likely to achieve high capacity utilisation (FLH). Unless the plant is not required for such purposes as provision of grid services or emergency power supply, it might turn out beneficial not to have a CHP plant in the system at all. In this case, the HOB would fulfil the remaining heat requirement not covered by waste heat from P2G and P2H units.

Decarbonisation with Power-to-Heat and Power-to-Gas. The results of a sensitivity analysis in the scenario 'P2H + P2G-HP first' are shown in Figure 9. In case of decarbonisation of the modelled district when heat is generated by HOBs only (without CHP), and the system is decarbonised using P2H, then a large 6.5 MW P2G and 15 MW wind power capacity would be required. This requirement decreases substantially with first 1,500 kW of HP installation, as displayed in Figure 9, showing a clearly decreasing trend in needed capacity for both P2G and wind power installations, until flattening after P2H installations reach 3 MW.

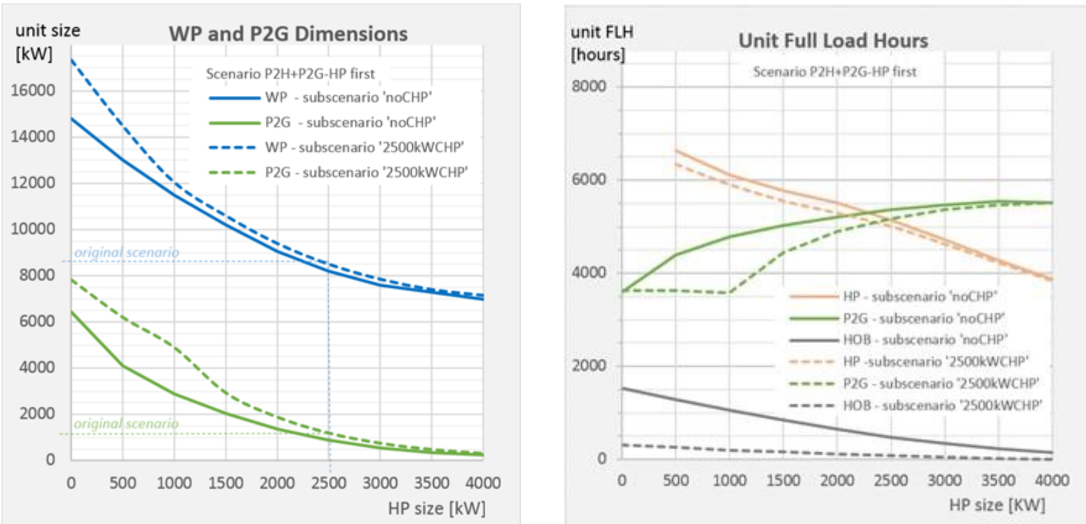


Figure 9. HP vs. needed P2G and wind power capacities to reach complete decarbonisation of heating (left) and corresponding FLH of heat production units (right)

Compared to the original scenario 'P2H + P2G-HP first', keeping the HP at 2,500 kW but leaving the CHP out would have decreased the needed WP installation by 300 kW to 8,200 kW and P2G installation by 320 kW_e to 880 kW_e nominal sizes, which is shown in Figure 9. For very large HP installations, over 3,500 kW, this difference would more or less disappear. However, at smaller HP installations, this dimensioning difference, i.e., saving, would have been much larger, over 2,000 kW of the needed P2G and 1,500 kW of the needed wind power capacity if capacity of P2H in the system would only be 500 kW. This clear saving would however come with the loss of capacity for emergency reserves or grid services the CHP could provide for the decarbonised system.

Decarbonisation with Power-to-Heat and excessive wind power production. A complete decarbonisation, i.e., 100% or more reduction in the total CO_2 emissions of the district energy system can also be reached with only P2H and excess wind power, without using P2G. The scenario 'P2H-HP first' was further analysed for this case, for various nominal sizes of the local wind power installation. The local wind power was utilised to cover local electricity consumption as well as consumption of the 2,500 kW P2H installation, and excess wind power was fed to external electrical grid within the limits of identified existing grid interface. The fed wind power replaces average grid power production, and corresponding national grid CO_2 reduction was accounted for. The results of this sensitivity analysis in the 'P2H-HP first' scenario, including the sensitivity to the CO_2-emission factors, are shown in Figure 10.

In this case, the district energy system could efficiently reach a complete decarbonisation if the national grid had considerable CO_2 emissions that could be reduced. For EU-average power grid emissions (296 g CO_2/kWh in 2016 [63]), a full decarbonisation could be reached if the local wind power installation capacity was increased from 5,700 kW to 7,000 kW, reaching 20% over-production annually. For the Finnish power grid, with lower average emission factor (113 g CO_2/kWh in 2016 [63]), the increase in local wind power installation capacity has to be greater, up to 9,000 kW, reaching 50% annual over-production.

However, for a practically carbon-free power grid like in Sweden (13 g CO_2/kWh in 2016 [63]), this indirect way of decarbonisation could not be utilized, since practically no additional carbon reduction would be achievable. Consequently, in such clean power system, a complete decarbonisation of the heating sector cannot be reached by simply feeding wind power into the clean power grid, and decarbonisation measures must instead be taken on the heating itself, e.g., by increasing capacity of HPs and utilization of green fuels.

In addition, the use of larger wind power installations resulted in strongly increasing curtailment losses, where 15% of added wind power was lost at a 9,000 kW wind power installation, and 60% of added wind power was lost at a 15,000 kW wind power installation. These significant curtailment losses could be avoided using the P2G installations.

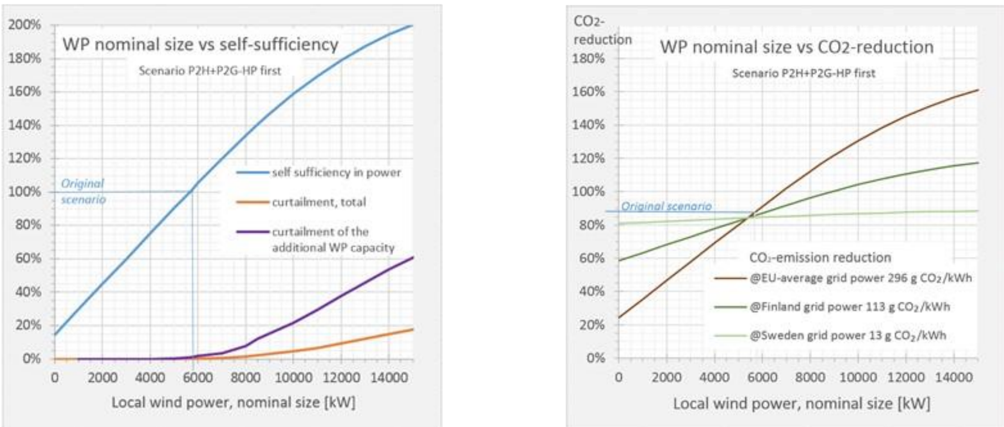


Figure 10. Impact of wind power generation capacity on district's self-sufficiency level (left) and total CO_2 emission reduction of the corresponding district energy system (including heat and electricity) using P2H

Comparison to earlier studies

The earlier study of Kötter *et al.* [32] found that regional electricity and heat demand could be covered by 100% RES also in the Rhineland Palatine region with help of P2G and P2H, even if their study did not explicitly investigate DH. In their cost-optimized wind-scenario, 56% of produced energy was covered with wind power and 19% with PV, the rest being hydropower and gas-fired CHP. In our study, no hydropower was assumed to be available. In our 'P2H-only' scenarios, with P2H as baseload, 84% of local CO_2 emission reduction was obtained using PV and wind power generation. Adding P2G storage further decreases the emissions to negative total emissions. In our study, the PV panels were installed on roofs of public buildings, which limited the share of PV output in total generation (6% 'P2G HP-first' scenario) and the share of wind power was larger. It is likely that availability of roof surface for PV installation limited the output of PV.

In our study, by meriting heat pump production, CHP production can be significantly decreased. Similar need for decreasing CHP production to was also observed by Salpakari *et al*. [43], who proposed that replacing CHP with P2H should be studied. In one of their renewable energy scenarios, significant loss of CHP production was found when used together with P2H, which made the configuration unprofitable. The full load hours used in the study of Salpakari *et al*. [43] were in line with the results of our study for the scenarios with prioritized heat pump and CHP, but not utilising P2G. Salpakari *et al*. [43] did not reach 100% decarbonization in their study, most likely because P2G was not investigated by them.

CONCLUSIONS

DH production in Europe is still largely covered by fossil fuels most often by natural gas. In Northern Europe, biomass accounts for most of the baseload heating. This study shows that a complete decarbonisation of the example district's power and heating energy can be reached even without the availability of biomass, if sufficient P2H and P2G capacity is integrated to the DH grid, and sufficiently more wind- and solar power is installed or contracted to replace all the fossil fuels. To reach this target, the P2H and P2G capacity, together with the legacy gas-fired CHP and HOB, must be coordinated and flexibly operated, which ensures that both the extensive wind- and solar power is used and both heating and power needs as well as hard power grid limitations are met.

It was shown that the merit order of the polygeneration, normally meriting CHP as baseload, should be changed towards P2H and P2G as baseload and CHP as intermittent or peak unit to avoid expensive over-investments to wind and P2G capacity. By meriting HP production, CHP production can be significantly decreased, which decreases the need for CO_2 reduction and SNG in the system. This leads to both reduced P2G capacity and reduced electricity need for P2G, which again decreases the need for wind power.

Ultimately, the need for P2G capacity and wind power could be further reduced, if the polygeneration system is operated completely without a CHP unit, relying only on the P2H, P2G and HOB heating capacities. However, leaving out the CHP unit might not always be possible, as it would reduce the amounts of emergency reserves and grid services available to the power system below a certain security level.

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NOMENCLATURE

c_p	heat capacity	[J/kgK]
$\dot{m}$	mass flow	[kg/s]
P	electric power	[W]
Q	heat power	[W]

r	power-to-heat ratio	-
T	absolute temperature	[K]

Greek letters

α	excess air coefficient
η	dimensionless degradation factor

Subscripts and superscripts

CHP	combined heat and power
cons	consumption
DH	district heat
e	electrical (capacity)
HP	heat pump
return	return
sink	sink
source	source
supply	supply

Abbreviations

CHP	Combined Heat and Power
COP	Coefficient of Performance
DH	District Heating
FLH	Full Load Hours
HHV	Higher Heating Value
HOB	Heat Only Boiler
HP	Heat Pump
HX	Heat Exchanger
LCOE	Levelized Cost of Energy
LHV	Lower Heating Value
NG	Natural Gas
P2G	Power-to-Gas
P2H	Power-to-Heat
PEM	Polymer Electrolyte Membrane
RES	Renewable Energy Sources
PV	Photovoltaic
SNG	Synthetic Natural Gas
WE	Water Electrolyser

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APPENDIX

Duration curves for the district heat production of the scenarios