Joint utilization of demand side flexibility of heating devices and heating grids with benefits for energy suppliers and customers

by

Markus Puchegger
Forschung Burgenland GmbH
Campus 1, 7000 Eisenstadt / Steinamangerstraße 21, 7423 Pinkafeld, Austria
Phone: +43 664 1616656
Email: markus.puchegger@forschung-burgenland.at

ABSTRACT: The rising amount of fluctuating renewable energy sources have to be integrated in the energy system by an approach which considers common forms of final energy that one finds in buildings (electricity and heat). Different types of residential buildings and district heating systems were simulated to determine their behavior concerning different flexibility strategies in order to optimize their own consumption of on-site PV-production and load management as defined by the energy supplier. The simulation was done by means of a Matlab-tool for each case and was based on real prices (spot market and consumer prices). For objects without own production, the entire flexibility was used for optimizing the energy suppliers' contribution margin. Therefore, thermal storage has been loaded at times with the lowest spot prices (usually during the night). Objects with own production were optimized in a three-step-process. First, on-site production, consumption of household loads and heating demand have been predicted/estimated based on weather forecasts and historical data. As a second step, a time frame was defined in which the storage must not be loaded using electricity from the network due to having a low state of energy when surplus from own production was predicted. As a last step, excluding the time frame used for optimizing own consumption the storage was loaded at low spot market prices. District heating was analyzed in another way. Different production profiles including wind and PV (after optimization at object level) and a measured load profile of a district heating network were used to investigate its economic and technical effects when using it in power-to-heat facilities. At the end, investment decsions were considered, including the results of the simulation and delivering target investment costs for ICT-solutions and power-to-heat facilities.

1. INTRODUCTION

Due to the rising share of fluctuating renewable energy sources, electricity production will not be able to adjust to the demand at all times any longer in the future. Therefore, demand side flexibility has to be boosted. Demand side flexibility can be assessed according to different parameters. For example, such an assessment could look at the amount of power and energy that can be stored for use at different times, energy availability, operation constraints (i.e. minimum run time of heat pumps) and many other aspects. In particular, heating applications, which can be situated either in decentralized objects such as single-family-homes, multi-storey homes, industry and commerce facilities or in centralized objects such as district heating systems are seen as suitable for effectively realising demand side management in terms of power and energy. Due to the fact that thermal energy storage costs are much lower than costs of electro-chemical storage, especially since storage structures (hot water storage, thermal storage masses of buildings) are already in place and only have to be activated accordingly, simultaneous usage of thermal storage options is investigated.

On the other hand, the electricity market system has to be taken into account when considering a more flexible energy system. In the existing energy market mechanisms, optimization of electrically driven heat generation in decentralized objects has to be realized in accordance with two often contrary perspectives. The users comfort must not be affected negatively and in addition, when using distributed energy production in the objects (mainly photovoltaics, PV), the goal for the prosumer should be to increase the objects' immediate consumption so as to save network charges and taxes. For the energy supplier, the immediate consumption of self-produced electricity by prosumers leads to lower sales and therefore a smaller contribution margin. Nevertheless, the remaining flexibility after optimisation of the customers own consumption could be used for the supplier to make use of low energy price periods/daytimes in electricity wholesale.

In Austria, operators of heating grids often face another challenge. Subsidies only were granted for a certain amount of years. Without subsidies the local heating networks cannot be operated economically advantageous. Contrariwise, operators of fluctuating renewables (mainly wind) are not able to cover their maintenance cost due to low wholesale prices for energy and costs for balancing energy caused by these assets after the end of incentive tariffs. Not least, flexibility provided by thermal storage in combination with power-to-heat is also seen as a measure for supporting the grid and improving the local balancing of electricity production and consumption.

This paper shows options for and analyses the impacts of utilising demand side flexibility of heating devices and grids in a residential area and the economic effects for both parties when trying to get benefits for electricity suppliers and residential customers.

2. THE OBSERVED NETWORK AREA

2.1 GENERAL ASSUMPTIONS

Before describing the network area itself, some general assumptions are made concerning the framework of the study. For all simulations and calculations done, the general assumption is that economic data concerning the electricity market is based on a perfectly competitive energy market, which means in particular that any optimisation done for the observed area does not change general prices or other aspects of the market framework. In addition, network charges and taxes were only calculated when explicitly mentioned, in most of the cases, they can be seen as transitory items with no effect when changing load curves. For the technical part, it is assumed, that any optimisation does not violate electricity network conditions, every optimisation logic was made without any network calculations. All data used for the simulation is based on data available for the year 2015.

2.2 EXTERNAL FACTORS

Before defining the characteristics of the observed area, some general external simulation data is specified. One external data set used for the simulations was weather data, available in 10 min time intervals for temperature, humidity, wind speed and global irradiance (Ubimet, 2016). Hourly spot market prices from EEX for 2015 were used as electricity wholesale prices (EEX, 2015). For customers, the following prices were used for the study:

- Retail price including network charges and taxes: 20.08 ct/kWh
- Retail price energy: 6.15 ct/kWh
- Price for feed-in of PV-production: 6.00 ct/kWh

2.3 INFRASTRUCTURE

The observed network area includes 3,048 households with electrically relevant heat production. These heating applications are spread across different technologies, which are hot water boilers, heat pumps and night storage heaters. Hot water boilers are used in single family houses (SFH) as well as in dwellings (DW), heat pumps are only used in single family houses, night storage heaters only in dwellings. Heating demand of houses and dwellings was split in three categories according to their year of construction/refurbishment and is relevant for households with electrically relevant space heating. At the moment, on-site PV-production is only used in single family houses, in order to consider the expected changes in the Electricity Industry and Organisation Act (ELWOG), future usage for dwellings is considered. Overall, the following housing infrastructure is given in the basic scenario as shown in Table 1 .

Table 1 Housing infrastructure of the area

Type of household	Heating demand	Heat producer for space heating	Thermal power of heat producer for space heating	Hot water producer	Thermal power of hot water producer	Peak power of PV System	Heat storage Water (W) Heating Buffer (H)	Number of households within this type
[-]	[kWh/m²a]	[-]	[kW]	[-]	[kW]	[kW]	[l]	[pcs]
DW-1	Not relevant	-	-	Hot water boiler	4.5	0	W: 110 l	1,409
DW-2	19	Night storage heater	6.7	Hot water boiler	4.5	0	W: 110 l	183
DW-3	41	Night storage heater	9.7	Hot water boiler	4.5	0	W: 110 l	183
DW-4	101	Night storage heater	15.7	Hot water boiler	4.5	0	W: 110 l	853
SFH-1	19	Night storage heater	15.2	Hot water boiler	4.5	0	W: 300 l H: 400 l	32
SFH-2	41	Night storage heater	21.9	Hot water boiler	4.5	0	W: 300 l H: 600 l	32
SFH-3	101	Night storage heater	36	Hot water boiler	4.5	0	W: 300 l H: 800 l	144
SFH-4	19	Night storage heater	15.2	Hot water boiler	4.5	5	W: 300 l H: 400 l	4
SFH-5	41	Night storage heater	21.9	Hot water boiler	4.5	5	W: 300 l H: 600 l	4
SFH-6	101	Night storage heater	36	Hot water boiler	4.5	5	W: 300 l H: 800 l	16
SFH-7	41	Heat pump	7	Heat pump	7	0	W: 300 l H: 600 l	169
SFH-8	41	Heat pump	7	Heat pump	7	5	W: 300 l H: 600 l	19

The boiler house of the heating network is equipped with a 2.3 MW biomass boiler and a 2.4 MW back-up gas boiler.

2.4 ELECTRICITY CONSUMPTION

Electric power consumption of the single house was simulated with a separate tool according to Zeilinger, Groiß, & Schuster (2014) in 15-minute-time intervals. For accurate aggregation of the household profiles to a realistic load curve for the whole area, different profiles were used for each household in a way to get an aggregated profile which has the characteristic load profile of the H0 standard profile. Heating devices were not considered in this approach due to further consideration in the optimization. The average consumption for all households without heating devices is 1.748 kWh/a, the average consumption including heating devices is

8.415 kWh/a. Overall power consumption for the relevant households in the area is about 5.3 GWh (without heating) and 25.6 GWh (including heating).

2.5 HEATING CONSUMPTION

The supply region of the heating network does not only include households. Public facilities and trading companies are also connected. The load profile for the heating network was measured and is shown in the annual load duration curve (Figure 1) (Measurement_A, 2017).

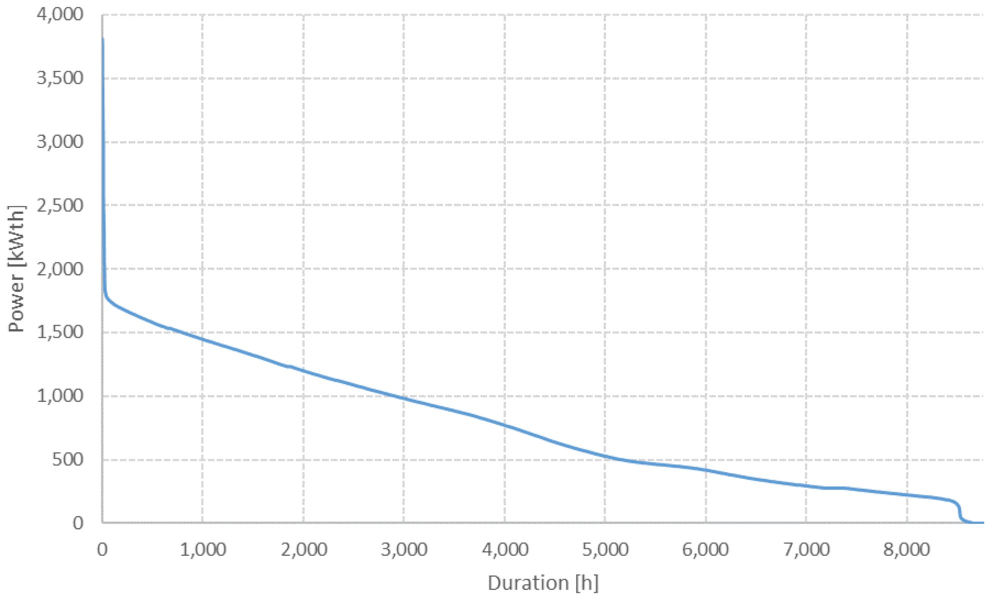

Figure 1 Annual load duration curve of the heating network

Overall heating consumption of the year is 6,636 MWh, whereas the seasonal distribution can be seen in Figure 2. Although highest demand is occurring during the heating season, there is a baseload in summer for warm water and other thermal demand (mainly public infrastructure).

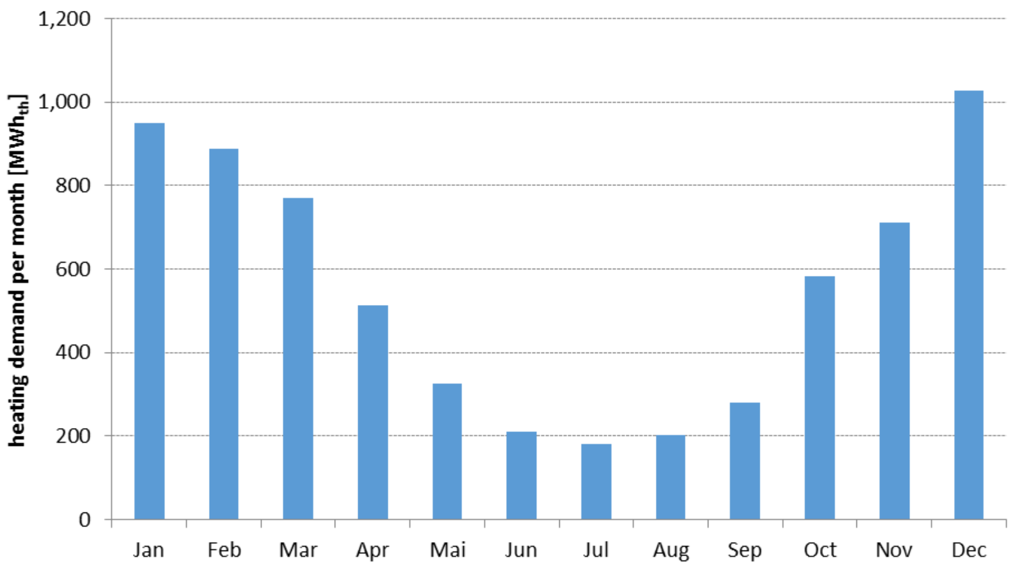

Figure 2 Heating demand per month

2.6 ELECTRICITY PRODUCTION

For the basic scenario it is assumed that app. 10 % of the single family houses own a PV-System with a nominal power of 5 kW_p. This assumption is based on the number of buildings in

Austria, which is 2,191,280 (Statistik Austria, 2017) and the installed capacity of PV on buildings in Austria, which is 1,037 MW_p (Biermayr, 2016), which leads to a share of app. 10 % of buildings with an average nominal power of 5 kW_p. For the area in focus that means, that from the 420 SFH, 43 are equipped with a solar power system, each producing 5 kW_p. Additional electricity production within the area is given by wind power, the nominal power of the wind production is varied according to different scenarios. Therefore, the annual measured energy production of a wind park was divided by its nominal power, to get the specific power, which was multiplied by the assumed power in the scenario to calculate its absolute load curve. Within the year that was measured the wind park came to 1.154 full load hours (Measurement_B, 2016).

3. OPTIMIZATION OF HEATING DEVICES IN HOUSEHOLDS

3.1 OPTIMIZATION TOOL

Calculation of possible optimisation of heating devices in households was done by a Matlab tool using various input and output data. The tool is already described in (Puchegger, Nacht, & Weißenbacher, 2017), however, for better legibility, the optimisation logic is described again in the paper in hand. Basic assumptions for the acceptance of optimisation in households are that the customer will have no comfort losses and no financial disadvantages. As the point of time of the energy usage is not effecting the costs for households in the present market model, positive financial effects can only be provided for the households when producing electricity on site (via PV). Nevertheless, any savings generated for the energy provider could also be shared with the customers. Therefore, also effects on optimising households without own production are investigated. The following parameters build the basis for the optimisation (Table 2):

Table 2 Input parameters for Matlab tool

Parameter	Source
Electric load curve of the building excluding electrical driven heat production	Load curve tool (Zeilinger, Groiß, & Schuster, 2014)
Thermal losses of the building/dwelling in 15 min time intervals	Simulation in Polysun (Urschler & Schaffer, 2016)
Thermal parameter for heating buffers in buildings	(Urschler C. , 2016)
Technical parameters of heat pumps, heat water boiler and night storage heater	(Urschler C. , 2016)
Production of PV system	Simulation in PV-Sol Expert
Wholesale prices for electrical energy	(EEX, 2015)

Focus of optimization efforts is to maximize the on-site production (if there is any) in a first step and then using the remaining flexibility to load the hot water storages at times of low energy prices on the wholesale market. The calculation of the optimization is completed in the following steps:

1. Calculation of the residual load P_R [W] for each time interval by building the difference between the electrical load curve excluding the electrically driven heat production P_L [W] and the on-site PV production P_{PV} [W] (Equation 1).

$$P_R = P_L - P_{PV} \tag{1}$$

2. Definition of a turn-on threshold f_{ON}, which can be defined as a value between 0 and 1. The heating device is working when the surplus of the PV production P_S [W] multiplied with the turn-on threshold is bigger than the nominal electrical power consumption of the heating device P_{EL} [W]. The operating factor f_{OP} describes the running time of the heating device within the 15 min time interval (important for heat pumps) (Equation 2).

$$P_{HD} = \begin{cases} 0, & | \; f_{OP} \cdot P_{EL} > P_S \cdot f_{ON} \\ P_{THERM} \cdot f_{OP}, & | \; P_{EL} \cdot f_{OP} \leq P_S \cdot f_{ON} \end{cases} \quad (3)$$

3. Optimisation for the energy supplier is closely linked to spot market prices for the present and future time intervals within the forecast horizon t_{FC} (24 h for day ahead prices). When optimizing for the energy supplier, the following logic is used (Equation 3). The price optimisation factor f_{PO} can be set between 0 and 1 and defines the price limit according to the average price within the forecast horizon.

$$P_{HD} = \begin{cases} 0, & \left| \; p(t) > \dfrac{\sum_{x=t}^{t+t_{FC}} p(x)}{t_{FC}} \cdot f_{PO} \right. \\ P_{THERM}, & \left| \; p(t) \leq \dfrac{\sum_{x=t}^{t+t_{FC}} p(x)}{t_{PROG}} \cdot f_{PO} \right. \end{cases} \quad (3)$$

4. The connection between the thermal output of heat pumps P_{THERM} [W] and the electrical power consumption P_{EL} [W] is given by a function ε_{SYS} of source temperature T_S [K], heat dissipation temperature T_D [K] and technical parameters of the heat pump p_{HP} (Equation 4). For other heating devices, the thermal output is equal to the electrical power consumption.

$$P_{EL}(t) = \frac{P_{THERM}(t)}{\varepsilon_{SYS}(t, T_S, T_D, p_{HP})} \quad (4)$$

5. Equation 5 defines the limits of the heating storage; the current status of the storage has to be between the minimum and maximum energy limit. The energy balance depends on the status at time interval t-1 $E_{ST}(t-1)$ [Wh], energy input to the storage E_{IN} [Wh], energy taken out of the storage E_{OUT} [Wh] and storage losses E_{LOSS} [Wh].

$$E_{ST}(t) = E_{ST}(t-1) + E_{IN}(t) - E_{OUT}(t) - E_{LOSS}(t) \quad (5)$$

6. During optimisation, at the beginning of each time interval it shall be decided which optimisation mode (Equation 2 or 3) is to be applied. To ensure that the storage can absorb the maximum amount of energy and to prioritize the producers' own PV production consumption, the storage shall have an energy status that is as low as possible before any expected PV-surplus becomes available. This can be done by a third optimisation mode, a locking mode, where the heating device's default state is 'off', except the storage has reached its minimum state. The length of this locking mode can be defined using forecasts for production driven by own consumption and heating demand. Here, the status of the storage at the beginning of the own consumption (first time interval of the day when $P_{EL} \cdot f_{OP} \leq P_S \cdot f_{ON}$) should be as defined in Equation 6. $E_{ST}(t0)$ [Wh] defines the status of the storage at the beginning of the heat production by own consumption according to Equation 2; $E_{IN}(d)$ $[\frac{Wh}{d}]$, $E_{OUT}(d)[\frac{Wh}{d}]$, $E_{LOSS}(d)[\frac{Wh}{d}]$ describe the energy flow into the storage, coming out of the storage and the storage losses until $f_{OP} \cdot P_{EL} > P_S \cdot f_{ON}$.

$$E_{ST}(t0) = \begin{cases} E_{ST,min} & | \; \& \; E_{IN}(d) > E_{OUT}(d) - E_{LOSS}(d) \\ E_{IN}(d) - E_{OUT}(d) - E_{LOSS}(d) & | \; \& \; E_{IN}(d) \leq E_{OUT}(d) - E_{LOSS}(d) \end{cases} \quad (6)$$

7. Finally, the operation mode mod_{HD} of the heating device for each time interval is defined in the equation below (Equation 7):

$$mod_{HD}(t) = \begin{cases} "Consumer", |P_{EL} \cdot f_{OP} \leq P_S \cdot f_{ON} \\ "Supplier", |P_{EL} \cdot f_{OP} > P_S \cdot f_{ON} \cap t(d) < t0 \\ "Locked", |P_{EL} \cdot f_{OP} > P_S \cdot f_{ON} \cap t(d) \geq t0 \end{cases} \quad (7)$$

As explained in (Puchegger, Nacht, & Weißenbacher, 2017), the following factors provide the economically most advantageous results:

f_{ON} =0.25

f_{PO} =0.7

Figure 3 shows an example of an optimized day. As the heating device is running during the night when prices are at their lowest, the following locked mode only leads to avoiding completely empty storage. After reaching f_{ON} with production surplus, the storage fills up completely. Losses and outputs from storage are fully compensated during the time of own production surplus.

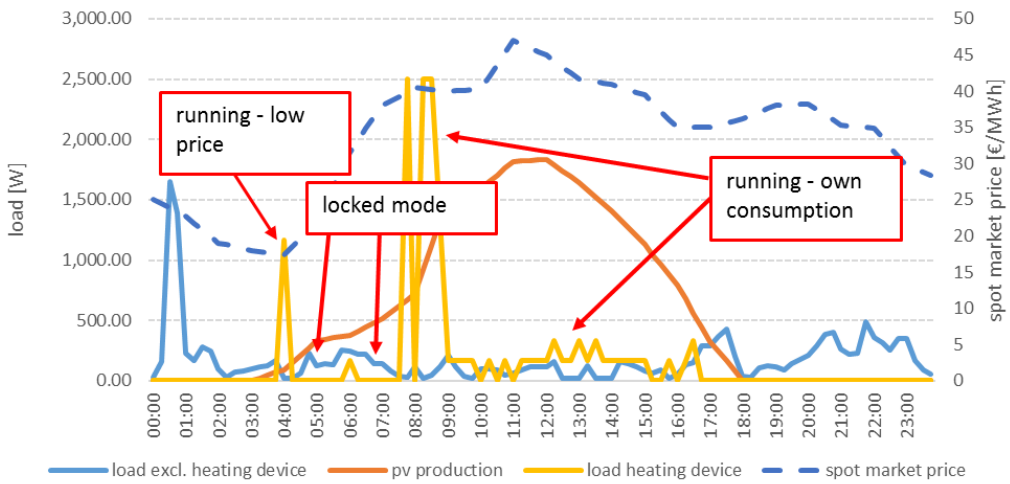

Figure 3 Example for optimization of heat water storage

3.2 RESULTS OF OPTIMISATION IN HOUSEHOLDS

Table 3 shows the economic results for households and energy suppliers in an optimized setting. The baseline scenario for households is the on-off control for the storage, where the heating device switches on when the storage reaches its minimum and switches of when it reaches its maximum. The baseline scenario for the energy supplier is different for households with own consumption, where it is assumed that the households optimize their own consumption individually.

Table 3 Economic results for optimization

Type of household	Surplus per household for customer	Surplus per household for supplier	Number of households within this type	Surplus for all house-hold within this type	Surplus for supplier within this type	Overall sur-plus	Average overall sur-plus per household
[-]	[€/a]	[€/a]	[pcs]	[€/a]	[€/a]	[€/a]	[€/a]
DW-1	0	10.51	1,409	0	14,808.59	14,808.59	10.51
DW-2	0	51.64	183	0	9,450.12	9,450.12	51.64
DW-3	0	68.42	183	0	12,520.86	12,520.86	68.42
DW-4	0	106.21	853	0	90,597.13	90,597.13	106.21
SFH-1	0	56.70	32	0	1,814.40	1,814.40	56.70
SFH-2	0	70.69	32	0	2,262.08	2,262.08	70.69
SFH-3	0	103.85	144	0	14,954.40	14,954.40	103.85
SFH-4	75.49	60.81	4	301.96	243.24	545.20	136.30
SFH-5	76.11	80.84	4	304.44	323.36	627.80	156.95
SFH-6	182.47	272.48	16	2,919.52	4,359.68	7,279.20	454.95
SFH-7	0	25.83	169	0	4,365.27	4,365.27	25.83
SFH-8	22.41	20.08	19	425.79	381.52	807.31	42.49
Sum			**3,048**	**3,951.71**	**156,080.65**	**160,032.36**	**52.50**

The table shows, that households with night storage heating have the highest economic impact concerning optimization. It can also be seen that the main savings potential is on the suppliers' side, even for households improving their own consumption (except type SFH-8 with the heat pump, where the savings are nearly equal). It can be said, that the amount of 52.50 €/a has to refinance possible upgrades of smart meters / ICT-connections and other costs for optimizing the heating devices' loads.

Due to the small share of PV-production within the area, the locally available surplus of PV on an aggregated level is negligible. Without optimization, 325 kWh per year would leave the area, whereas with optimization the amount is slightly higher (361 kWh).

In addition to the baseline scenario, a PV expansion scenario was analyzed, where the number of PV systems is increased within the area by 10 % points due to better economic efficiency (lower future investment prices, higher own consumption thanks to cooperation with the energy supplier). This means that in this scenario, 20% of SFH are using PV. In addition, the scenario assumes, that due to the modification of the ELWOG, also residents in dwellings are using PV in the future (10 % of the dwellings in the scenario, 2.5 kW_p for each system). The surplus for the supplier due to optimization would nearly stay the same with 158,411.62 €/a, whereas the households' surplus would grow to 11,050.20 €/a, overall surplus for both would be 169,461.82 €/a. Average overall surplus per household would be 55.60 €/a. The higher share of PV in the system would lead to a surplus of 85 MWh/a before optimization and 80.9 MWh/a after optimization.

4. OPTIMIZATION OF HEATING GRID

4.1 WIND AS POWER-TO-HEAT SOLUTION IN A HEATING GRID

For the integration of renewable electricity in district heating, some additional scenarios were simulated based on the current system configuration as described in 2.3. As more and more wind parks are losing their promotional feed in tariffs due to expiration of the funding period, big amounts of fluctuating production will enter the free market. Otherwise during low market prices and due the integration of wind energy in the balance groups of the energy suppliers, the economic situation for wind farm operators is becoming tight, other possibilities than selling energy on the wholesale market for the integration of wind energy are essential. For the wind farm analysed, the weighted average price for selling energy on the wholesale market for 2015 would have been 29.36 €/MWh; when including costs for the balancing energy arising from the discrepancy between real forecast and production the weighted average price would even shrink to 24.51 €/MWh. At first sight this price seems to be much lower, compared with heat production costs of local heat networks , even though investment costs and - depending on the situation – maybe even network charges have to be considered. Therefore, a deeper analysis is done for the combination of wind and heating grids within this chapter.

Essential input for economic assessment is the heat production costs for power-to-heat compared to the reference scenario. As the costs for heat production in heating networks strongly depend on the technology applied, alternative heating prices are varied. Outputs are cost limits for upgrading the boiler house with electrically driven heat producer(s) and the amount of energy, which can be replaced by power-to-heat. The latter is linked to the simultaneity of heating demand and wind production and is determined through the following steps.

1. Comparison between wind power in the interval $P_W(t)$ [W] and nominal electric power of the heating device $P_{El.Pth,nom}$ [W] according to Equation 9, where $P_C(t)$ [W] is the electric power, which can be converted into heat.

$$P_{C,1}(t) = \begin{cases} P_W(t) \mid P_W(t) \le P_{El.Pth,nom} \\ P_{El,Pth} \mid P_W(t) > P_{El,Pth,nom} \end{cases} \tag{9}$$

2. Comparison with the heating demand $P_{HD}(t)$ [W] according to Equation 10 under consideration of the system efficiency $\varepsilon_{SYS}(t)$ gives the amount of heat, which can be delivered for the heating grid by power-to-heat $P_{C,2}(t)$ [W] for the interval.

$$P_{C,2}(t) = \begin{cases} P_{C,1}(t) \cdot \varepsilon_{SYS} \mid P_{HD}(t) > P_{C,1}(t) \cdot \varepsilon_{SYS}(t) \\ P_{HD}(t) \mid P_{HD}(t) \le P_{C,1}(t) \cdot \varepsilon_{SYS}(t) \end{cases} \tag{10}$$

3. Electrical power input for Power-to-heat for each interval $P_{El,Pth}$ [W] is given by Equation 11.

$$P_{El,Pth}(t) = \frac{P_{C,2}(t)}{\varepsilon_{SYS}(t)} \tag{11}$$

1. Integration of the power used in power-to-heat facility according to Equation 12 (12) and 13 gives the electric energy used for power-to-heat $E_{El,Pth}$[Wh] and the thermal output energy $E_{C,2}$ [Wh].

$$E_{El,Pth} = \int_0^t P_{El,Pth} dt$$

$$E_{C,2} = \int_0^t P_{C,2} dt \tag{13}$$

According to Figure 1 and the price structure covering of the base load with power-to-heat could make sense. Therefore, two sizes of power-to-heat are examined, a smaller one with

500 kW and a bigger one with 1 MW nominal power (thermal). In addition, the power of the wind farm connected to the heating grid was varied between 1 MW and 10 MW. Figure 4 shows the amount of power-to-heat, which could be included into the heating grid and the percentage of the total heat demand.

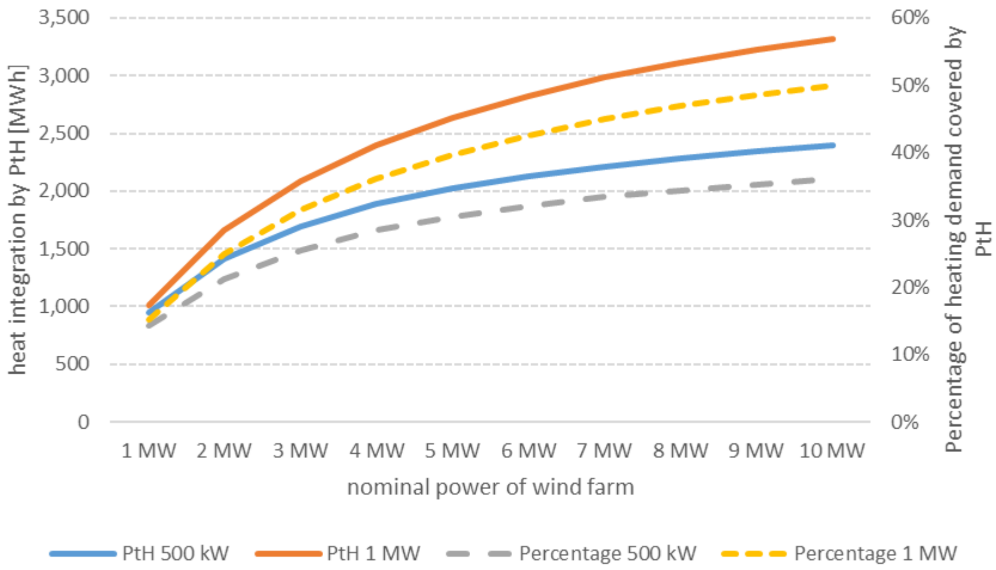

Figure 4 Heating demand covered by PtH from wind farms

Table 4 and Table 5 show the possible savings in heating costs through the usage of power-to-heat using the wholesale market price for wind and the price including balancing costs. It can be seen that the bigger the connected wind farm, the higher the nominal power of the power-to-heat device becomes and the higher the alternative heat price, the higher the savings are.

Table 4 Money savings through PtH per year using whole sale market price for wind

	Heat costs	Wind park size									
	€/MWh	1 MW	2 MW	3 MW	4 MW	5 MW	6 MW	7 MW	8 MW	9 MW	10 MW
PtH 500 kW	40	10,038	15,035	18,027	20,078	21,558	22,683	23,573	24,304	24,923	25,450
PtH 1 MW	40	10,710	17,667	22,204	25,517	28,049	30,071	31,730	33,116	34,290	35,295
PtH 500 kW	60	28,906	43,297	51,911	57,818	62,081	65,320	67,884	69,989	71,770	73,289
PtH 1 MW	60	30,843	50,874	63,941	73,482	80,772	86,595	91,373	95,365	98,744	101,640
PtH 500 kW	80	47,773	71,558	85,796	95,559	102,604	107,957	112,194	115,673	118,617	121,127
PtH 1 MW	80	50,975	84,082	105,677	121,447	133,496	143,119	151,016	157,614	163,198	167,985

Table 5 Money savings through PtH per year using price for wind including balancing costs

	Heat costs	Wind park size									
	€/MWh	1 MW	2 MW	3 MW	4 MW	5 MW	6 MW	7 MW	8 MW	9 MW	10 MW
PtH 500 kW	40	14,613	21,888	26,244	29,230	31,385	33,023	34,318	35,383	36,283	37,051
PtH 1 MW	40	15,592	25,719	32,325	37,149	40,834	43,778	46,193	48,212	49,920	51,384
PtH 500 kW	60	33,481	50,150	60,129	66,970	71,908	75,660	78,629	81,067	83,130	84,890
PtH 1 MW	60	35,725	58,927	74,062	85,114	93,558	100,302	105,836	110,460	114,374	117,729
PtH 500 kW	80	52,349	78,411	94,013	104,711	112,430	118,297	122,939	126,752	129,977	132,728
PtH 1 MW	80	55,857	92,135	115,798	133,079	146,281	156,826	165,479	172,709	178,828	184,074

Analogous to the studies of the usage for wind in power-to-heat devices (Equations 9 – 13), the usage of PV-surplus is examined. Therefore, Equation 9 is changing to Equation 14, where $P_{PV,S}(t)$ is the PV-surplus of the time interval.

$$P_{C,1}(t) = \begin{cases} P_{PV,S}(t) \mid P_{PV,S}(t) \leq P_{El.Pth,nom} \\ P_{El,Pth} \mid P_{PV,S}(t) > P_{El,Pth,nom} \end{cases} \quad (14)$$

If only PV-surplus is used in PtH, the amount of energy used in the power-to-heat device is much lower than that for wind. Depending on the size of the power-to-heat device and the PV-feed-in curve before and after optimization, according to chapter 3 of the PV-expansion scenario, heating demand covered by solar powered PtH is shown in Figure 5. As expected, the amount of energy usable for PtH is by far lower than in any wind scenario.

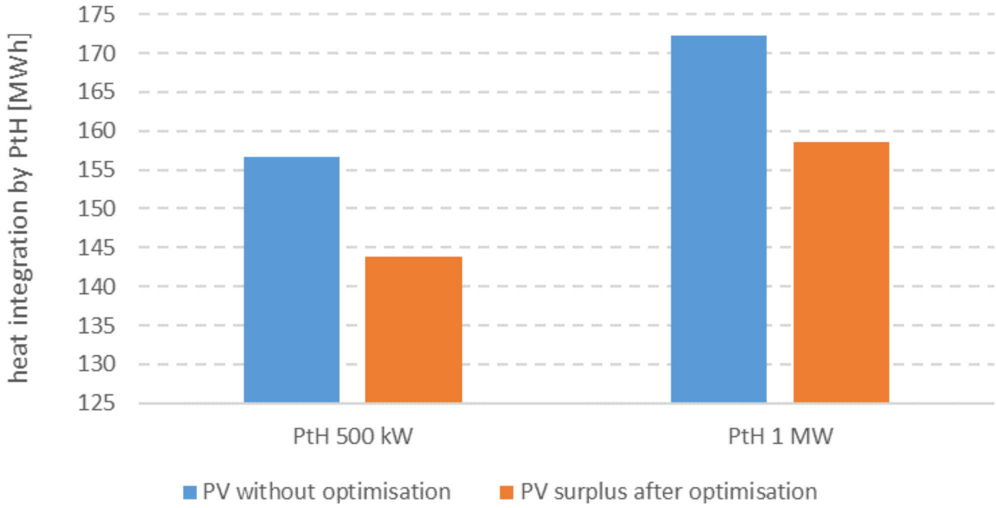

Figure 5 Heating demand covered by PtH from PV-surplus

4.2 COMBINED USAGE OF WIND AND PV-SURPLUS IN HEATING GRIDS

In this chapter, the combined usage of wind and PV-surplus for the PV expansion scenario after optimization of households is examined. Therefore, Equation 9 and 14, respectively, are changing to Equation 15, the other steps are following analogous to the previous examinations.

$$P_{C,1}(t) = \begin{cases} P_{PV,S}(t) + P_W(t) & |P_{PV,S}(t) + P_W(t) \leq P_{El.Pth,nom} \\ P_{El,Pth} & |P_{PV,S}(t) + P_W(t) > P_{El,Pth,nom} \end{cases} \tag{14}$$

Figure 6 shows the combined heating demand covered by PtH from wind farm and PV-surplus and the growth due to PV-integration in addition to the wind park.

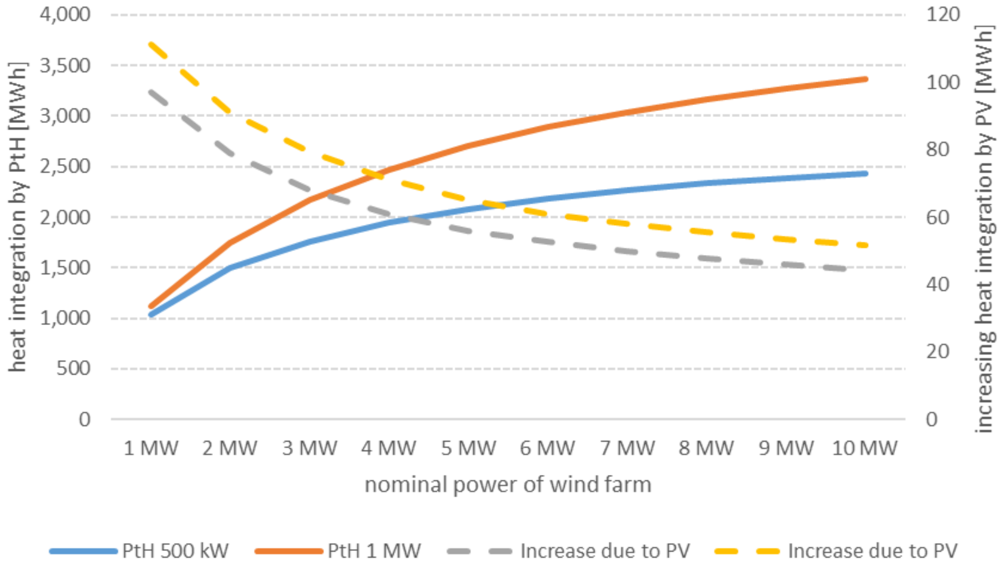

Figure 6 combined heating demand covered by PtH from wind farm and PV-surplus

This also leads to a growth of possible money savings thanks to power-to-heat as shown in Table 6 and Table 7.

Table 6 Money savings through PtH per year using wholesale market price for wind and PV-surplus

	Heat costs	Wind park size									
	€/MWh	1 MW	2 MW	3 MW	4 MW	5 MW	6 MW	7 MW	8 MW	9 MW	10 MW
PtH 500 kW	40	11,071	15,874	18,751	20,726	22,152	23,242	24,104	24,813	25,411	25,922
PtH 1 MW	40	11,892	18,637	23,049	26,273	28,743	30,720	32,347	33,708	34,859	35,845
PtH 500 kW	60	31,881	45,712	53,998	59,684	63,792	66,931	69,413	71,453	73,177	74,648
PtH 1 MW	60	34,247	53,668	66,374	75,659	82,772	88,465	93,150	97,068	100,383	103,224
PtH 500 kW	80	52,691	75,550	89,245	98,642	105,432	110,620	114,722	118,093	120,943	123,373
PtH 1 MW	80	56,601	88,699	109,700	125,044	136,800	146,210	153,952	160,428	165,907	170,603

Table 7 Money savings through PtH per year using price for wind including balancing costs and PV-surplus

	Heat costs	Wind park size									
	€/MWh	1 MW	2 MW	3 MW	4 MW	5 MW	6 MW	7 MW	8 MW	9 MW	10 MW
PtH 500 kW	40	16,117	23,110	27,299	30,173	32,250	33,837	35,092	36,123	36,995	37,738
PtH 1 MW	40	17,313	27,132	33,555	38,249	41,845	44,724	47,092	49,073	50,748	52,185
PtH 500 kW	60	36,927	52,948	62,545	69,131	73,890	77,526	80,400	82,763	84,761	86,464
PtH 1 MW	60	39,668	62,163	76,881	87,635	95,874	102,469	107,894	112,433	116,273	119,563
PtH 500 kW	80	57,737	82,786	97,792	108,089	115,530	121,214	125,709	129,403	132,527	135,189
PtH 1 MW	80	62,022	97,194	120,206	137,020	149,902	160,214	168,697	175,793	181,797	186,942

Subsequently, the consideration of network charges for power-to-heat integration in heating networks is analyzed. Therefore, energy related network charges for network level 5 are added to the market price / price including balancing costs as shown in Table 8. It is assumed that no power related network fees are affected by power-to-heat, e.g. according to an interruptible tariff (SNE-VO, 2015).

Table 8 Energy related network charges

Component	Charge in network level 5 [ct/kWh]
Grid usage charge	1.09
Network loss charge	0.074
Electricity duty	1.5
Ecoelectricity fee	0.274
Sum	**2.938**

The results show that integration of power-to-heat including network charges only makes sense when the alternative heat production price is 60 €/MWh or higher (Table 9 and Table 10).

Table 9 Money savings through PtH per year using wholesale market price for wind and PV-surplus including network charges

	Heat costs	Wind park size									
	€/MWh	1 MW	2 MW	3 MW	4 MW	5 MW	6 MW	7 MW	8 MW	9 MW	10 MW
PtH 500 kW	40	-19,499	-27,958	-33,026	-36,504	-39,017	-40,936	-42,454	-43,702	-44,757	-45,656
PtH 1 MW	40	-20,946	-32,824	-40,596	-46,274	-50,625	-54,107	-56,972	-59,369	-61,396	-63,134
PtH 500 kW	60	1,311	1,880	2,221	2,454	2,623	2,752	2,854	2,938	3,009	3,070
PtH 1 MW	60	1,408	2,207	2,729	3,111	3,404	3,638	3,831	3,992	4,128	4,245
PtH 500 kW	80	22,121	31,718	37,467	41,412	44,263	46,441	48,163	49,579	50,775	51,795
PtH 1 MW	80	23,763	37,238	46,055	52,497	57,432	61,383	64,633	67,352	69,652	71,623

Table 10 Money savings through PtH per year using price for wind including balancing costs and PV-surplus including network charges

	Heat costs	Wind park size									
	€/MWh	1 MW	2 MW	3 MW	4 MW	5 MW	6 MW	7 MW	8 MW	9 MW	10 MW
PtH 500 kW	40	-14,452	-20,723	-24,479	-27,056	-28,919	-30,342	-31,467	-32,392	-33,173	-33,840
PtH 1 MW	40	-15,525	-24,329	-30,089	-34,298	-37,523	-40,104	-42,227	-44,004	-45,507	-46,794
PtH 500 kW	60	6,357	9,116	10,768	11,902	12,721	13,347	13,842	14,249	14,592	14,886
PtH 1 MW	60	6,829	10,702	13,236	15,087	16,506	17,641	18,575	19,357	20,018	20,584
PtH 500 kW	80	27,167	38,954	46,015	50,860	54,361	57,036	59,150	60,889	62,358	63,611
PtH 1 MW	80	29,183	45,733	56,561	64,473	70,534	75,386	79,378	82,717	85,542	87,963

When considering network charges it becomes obvious that economic efficiency is hardly effected by the shortened (or negative) difference between the price for electricity and heat, in particular when $\varepsilon_{SYS} = 1$, which is generally given when using electrical direct heating as power-to-heat device. Using heat generation based on heat pumps could increase this number. Using a high temperature heat pump with an average performance coefficient of 2 would lead to the following figures shown in Table 11 and Table 12 which reflect savings although energy related network charges are also included. The savings are nearly the same as the savings without network charges for power-to-heat with a device in which $\varepsilon_{SYS} = 1$.

Table 11 Annual money savings through PtH using a heat pump applying wholesale market prices for wind and PV-surplus, including network charges

	Heat costs	Wind park size									
	€/MWh	1 MW	2 MW	3 MW	4 MW	5 MW	6 MW	7 MW	8 MW	9 MW	10 MW
PtH 500 kW	40	11,060	15,859	18,734	20,706	22,132	23,221	24,082	24,789	25,388	25,898
PtH 1 MW	40	11,881	18,619	23,027	26,248	28,716	30,691	32,317	33,676	34,826	35,812
PtH 500 kW	60	31,870	45,697	53,980	59,664	63,772	66,909	69,390	71,430	73,154	74,623
PtH 1 MW	60	34,235	53,650	66,353	75,634	82,745	88,436	93,119	97,036	100,350	103,190
PtH 500 kW	80	52,680	75,535	89,227	98,622	105,412	110,598	114,699	118,070	120,919	123,349
PtH 1 MW	80	56,590	88,681	109,678	125,020	136,773	146,182	153,922	160,396	165,874	170,569

Table 12 Annual money savings through PtH using a heat pump applying prices for wind, including balancing costs and PV-surplus, including network charges

	€/MWh	1 MW	2 MW	3 MW	4 MW	5 MW	6 MW	7 MW	8 MW	9 MW	10 MW
PtH 500 kW	40	13,584	19,477	23,007	25,430	27,181	28,518	29,575	30,444	31,179	31,806
PtH 1 MW	40	14,592	22,867	28,281	32,236	35,267	37,693	39,689	41,358	42,771	43,981
PtH 500 kW	60	34,393	49,315	58,254	64,388	68,821	72,206	74,884	77,085	78,945	80,531
PtH 1 MW	60	36,946	57,898	71,606	81,622	89,296	95,438	100,492	104,719	108,295	111,360
PtH 500 kW	80	55,203	79,153	93,501	103,346	110,461	115,895	120,193	123,725	126,711	129,257
PtH 1 MW	80	59,300	92,929	114,931	131,008	143,324	153,183	161,294	168,079	173,819	178,738

5. INVESTMENT CONSIDERATIONS

In chapter 5 some considerations about investment calculations based on the benefits determined in chapter 3 and 4 are done, both separately and aggregated. As determined, the average benefit for households when optimizing the PV expansion scenario would be 55.60 €/a. As the necessary investment costs for utilization of these flexibilities (mainly ICT-connections) is not clear now and has to be engineered in detail, the approach in this paper is to define target costs per household according to different payback periods. The calculation was done with an internal interest rate of 4 %. Figure 7 shows the cost limit per household according to accepted amortization periods.

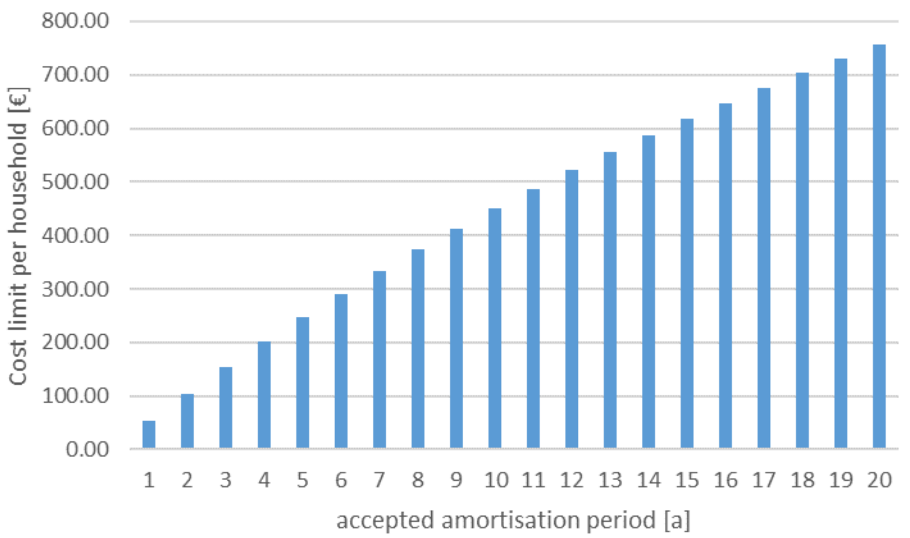

Figure 7 Target costs per household for accepted amortization periods for optimization

For the integration of power-to-heat by wind farms and surplus of PV, the same calculations were done. Only a few results are shown below, due to the amount of different wind scenarios.

Having a 2 MW wind turbine directly connected to the heating grid and using wholesale market prices, the following target costs can be shown for a 500 kW power-to-heat electric boiler (Figure 8):

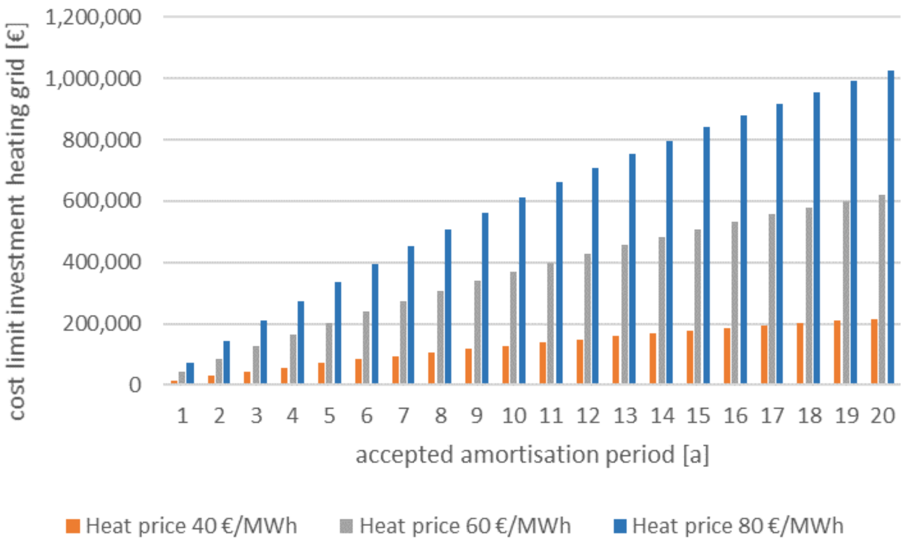

Figure 8 Target costs for electric boiler without network charges for electricity using 2 MW wind and PV-surplus

The usage of wind power of a wind farm with 6 MW nominal power and PV-surplus including network charges in a 500 kW high temperature heat pump has target investment costs as shown in Figure 9.

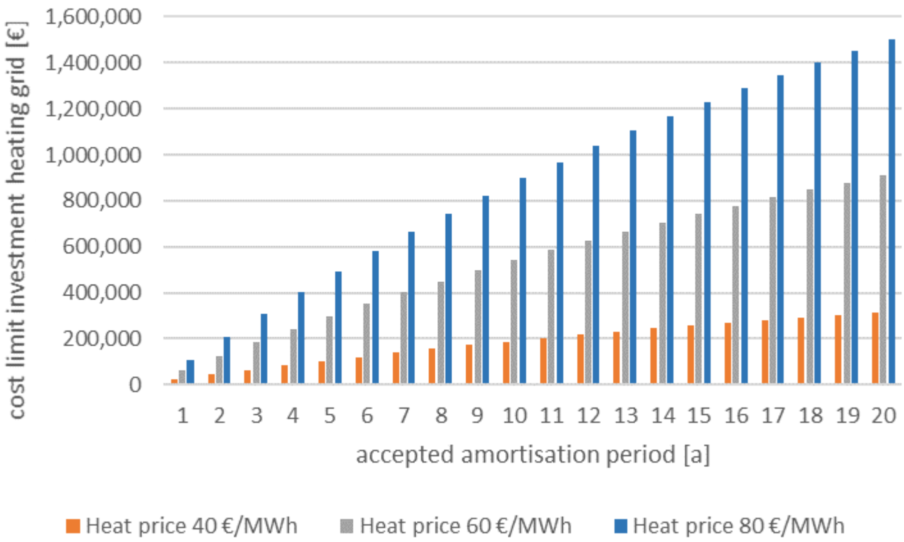

Figure 9 Target costs for heat pump including network charges for electricity using 6 MW wind and PV-surplus

Summarizing the yearly monetary advantages of the 3.048 optimized households and power-to-heat, overall target costs for investments can be estimated for 2 MW wind / electric boiler / excluding network charges as shown in Figure 10 and 6 MW wind / heat pump / including network charges as shown in Figure 11.

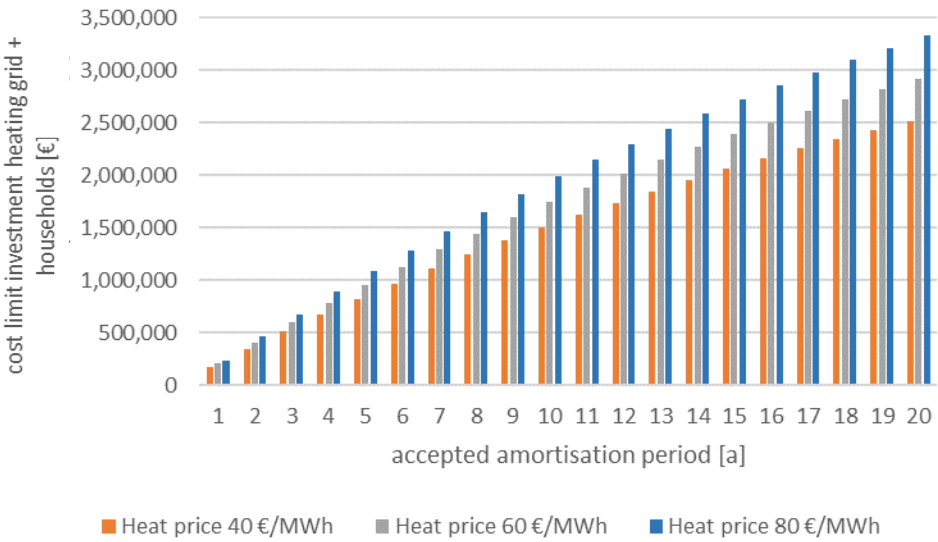

Figure 10 Summarized advantages for household optimization and Pth (2 MW wind turbine / electric boiler / excluding network charges)

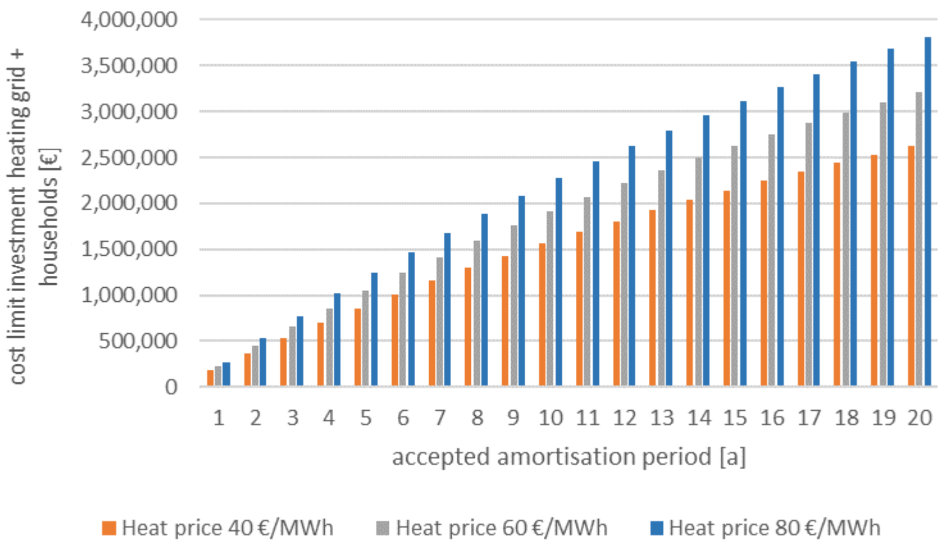

Figure 11 Summarized advantages for household optimization and Pth (6 MW wind park / heat pump / including network charges)

6. CONCLUSION AND OUTLOOK

The paper shows the effects of optimized usage of on-site PV production and power-to-heat in a network area. Whereas the optimization of households has to be done by a low cost approach according to quite low target costs per household, the target costs for power-to-heat are strongly connected with the scenario.

Generally, for power-to-heat using wind (and PV-surplus) the following aspects are pointed out:

- High amount of connected wind power to higher savings per year
- High common heat generation costs are positive for power-to-heat solutions

- For power-to-heat solutions which has to pay network charges, the efficiency of the power-to-heat device ε_{SYS} should be higher than 1 (usage of heat pumps).

Generally the paper gives some ideas about target costs for both solutions. To come to an investment decision, detailed planning - including real costs for the respective solutions - has to be prepared.

Concerning the simulation approach, the next steps will be the merging of the tools for heating grids and households in order to optimize both aspects in an integrated approach and examining whether this can lead to further synergy effects in the optimization when compared to step-by-step consideration.

7. LIST OF REFERENCES

Biermayr, P. (2016). Innovative Energietechnologien in Österreich - Marktentwicklung 2016. *Co-Authors: Christa Dißauer, Manuela Eberl, Monika Enigl, Hubert Fechner, Kurt Leonhartsberger, Florian Maringer, Stefan Moidl, Christoph Schmidl, Christoph Strasser, Werner Weiss, Patrik Wonisch, Elisabeth Wopienka*. Wien: Bundesministerium für Verkehr, Innovation und Technologie.

EEX. (2015). European Energy Exchange AG. *Marktdaten*. Leipzig, Deutschland.

Götz, M., Böttger, D., Kondziella, H., & Bruckner, T. (13. 04 2013). Economic Potential of the "Power-to-Heat" Technology in the 50Hertz Control Area. Dresden: University of Leipzig.

Measurement_A. (2017). Measurement Data of Heating Network.

Measurement_B. (2016). *Measurement data of a wind park*.

Puchegger, M., Nacht, T., & Weißenbacher, R. (2017). Konzept einer smarten Verknüpfung eines urbanan Strom- & Fernwärmenetzes zu einem funktionalen Stromspeicher. *Konferenz Güssing 17.* Güssing: GET GmbH.

SNE-VO. (2015). Systemnutzungsentgelteverordnung 2012 in der Novelle von 2015. Wien, Österreich.

Statistik Austria. (29. 05 2017). *Bestand an Gebäuden und Wohnungen nach Bundesländern*. Von Statistik Austria: http://www.statistik.at/web_de/statistiken/menschen_und_gesellschaft/wohnen/wohnungs_und_gebaeudebestand/index.html abgerufen

Ubimet. (2016). Weather Data. Wien: Ubimet GmbH.

Urschler, C. (2016). *Typical parameters of building service systems*. TBH Ingenieur GmbH.

Urschler, C., & Schaffer, B. (2016). Simulation of thermal losses. Polysun.

Zeilinger, F., Groiß, C., & Schuster, A. (12. - 14.. 02 2014). Detaillierte Modellierung des Haushaltsstromverbrauchs zur Untersuchung von Demand Side Management. Graz, Österreich: 13. Symposium Energieinnovation.