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Heating Sector Decarbonization With Renewable Gas and Power-to-Heat

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***Abstract*—Deep decarbonization, which comprehends activities whose aim is to reduce carbon dioxide emissions in all economic sectors, is necessary to reach the goals of the Paris agreement. Consumption of fossil fuels in individual buildings is an important source of emissions. In this paper we study the economic feasibility of decarbonizing heat generation in natural gas heated buildings in two European countries. Heat pumps and substitution of fossil natural gas by synthetic natural gas (SNG) are studied as solutions for decarbonization in both Finnish and German conditions. We find that in both countries the SNG solution substantially increases the consumer's heating costs. Heat pump turned out to be economically viable in Finland while in Germany the high surcharges on green electricity made the heat pump solution unattractive.**

Keywords decarbonization, grid tariff, heat pump, green gas, SNG, power-to-heat, heating

I. Introduction

In the EU, the transition into a low carbon society will cover all the societal sectors, including the heating and cooling of buildings. Long term targets in the heating sector aim for more renewable integration, with studies indicating a shift to (renewable) gas, heat pumps (HP), and district heating (DH)[1]. To enable a broader decarbonization and a 100% renewable energy system, heat storages and sector coupling measures such as combined heat-and-power (CHP), power-to-heat (P2H), and power-to-gas (P2G) are needed.

Natural gas plays an essential role in covering the space heating demand in EU-28: 43 % of the space heating demand was covered by natural gas in 2017 [2]. In the EU-28, the space heating accounted for 64 % (7,636 PJ) of the final energy consumption in residential sector in 2017 [3]. Therefore, natural gas heating is substantial source of greenhouse gas emissions. Gas space heating is especially dominant in Germany, Netherlands and the United Kingdom. In 2014, 49.8% of new homes installed natural gas boiler in Germany, where as heat pump was installed in one in five homes (21.5%) [4].

HP heating systems allow the use of renewable electricity in space heating. HP systems are popular and widely used for preparing domestic hot water and space heating in all over the Europe but especially in Nordic countries [5]. Total number of heat pumps in Europe increased 11% from 2016 to 2017 [6]. However, e.g. in Finland, heat pump sales have substantially increased (30% yearly increase in 2019) due to excellent profitability and new service models and in 2019 the total production corresponded to 15% of residential and service building stock heating [7]. The increase has been especially high in domestic ground source heat pumps [8]. In 2017, total number of heat pumps in Germany was 974,750 and in Finland 794,602 [9], i.e. approximately the same, although Germany's population was 15 times to Finland's population.

Heating costs are a significant expenditure for many facility owners and residents, and there is not much room for cost increases. In addition, added value of replacing oil and gas boilers and renovating existing buildings if not often seen [6]. Well-designed and coordinated tariff policies for power and gas grids could stimulate the shift towards energy-efficient heating based on 100% renewable energy. For most existing buildings, the gas boiler fed heating system could be combined with heat pumps. Heat pumps can deliver majority of needed heat energy and absorb excess grid or renewable power, while gas can serve peak heat consumption, reducing power grid constraints.

In this study, we show the impact of some tariff policies for gas and power grids on the heating customer's economy. For some residential building examples, we evaluate the building owner's willingness to invest in sector-coupling technologies such as building-integrated HP. We compare situation for a Nordic country and Germany, using their climate, building standards, and tariff policy differences.

Results show the economic decarbonization potential of the sector-coupling building heating solutions. We point out, how tariff policies could boost investment and high utilization of HP, and decrease GHG emissions. In addition, we show that expensive renewable gas does not lead to substantially higher heating costs.

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II. MATERIAL AND METHODS

A. *Gas and power tariff policies for residential heating*

The gas tariffs in our scenario calculations are listed in Table I below. In Germany and Finland, end customer tariffs are available for fossil natural gas (NG) and green biogas (BG). For Germany, the used gas tariffs are based on multi-family apartment price estimates, published for NG in [10]. BG tariff components are based on 100 euro/MWh offers from retailers[11] and the retail costs and network fees from the NG tariff structure. For Finland we used similar offers for NG and BG from local retailers to heating end customers.

Synthetic natural gas (SNG) produced in power-to-gas facilities is not yet available on the heating market, but we estimate the structure of possible SNG tariffs using the same retailer's markup and network fees. We estimated SNG end customer tariffs for an optimistic 100 euro/MWh production cost scenario [12] and a pessimistic 200 euro/MWh production cost scenario[13] [14].

TABLE I. GAS TARIFF SCENARIOS

Gas Tariff euro/MWh	Finland				Germany			
	NG80	BG90	SNG147	SNG272	NG56	BG100	SNG145	SNG264
Fossil or Green gas	Fossil	Green Biogas	Green SNG[b]	Green SNG[c]	Fossil	Green Biogas	Green SNG[b]	Green SNG[c]
Natural gas wholesales price or biogas/SNG production price	24,92 €	53,26 €	100,00 €[b]	200,00 €[c]	24,92 €	68,50 €	100,00 €[b]	200,00 €[c]
Retail costs and markup	3,00 €	3,00 €	3,00 €	3,00 €	3,00 €	3,00 €	3,00 €	3,00 €
Network fees	16,21 €	16,21 €	16,21 €	16,21 €	12,60 €	12,60 €	12,60 €	12,60 €
VAT 19% (on prev..items)					7,57 €	0,00 €	7,57 €	7,57 €
Energy taxes & levies	21,82 €	0,00 €	0,00 €	0,00 €	7,70 €	15,98 €	21,96 €	40,96 €
VAT 24% (on all items)	15,83 €	17,39 €	28,61 €	52,61 €				
Heating end customer tariff	81,78 €[a]	89,86 €[a]	147,82 €[b]	271,82 €[c]	55,79 €[a]	100,08 €[a]	145,14 €[b]	264,14 €[c]

a. According to offers from the market

b. Estimated future tariff, using lower range 100euro/MWh for the production price

c. Estimated future tariff, using higher range 200euro/MWh for the production price

The used power tariff in our scenario calculations are listed in Table II below.

TABLE II. POWER TARIFF IN THE SCENARIOS

Heat Pump Customers Power Tariff euro/MWh	Scenario 2019	
	Finland	Germany
Fossil or Green Power	Green	Green
Power Retail Energy	52,50 €	52,50[c] €
Network fees	25,32 €	30,00[c] €
EEG-surcharge and KWK-fee (Germany)		68,80 €
Other energy taxes & levies	22,58 €	20,50 €
VAT 24% (Finland)	24,10 €	
VAT 19% (Germany)		32,64 €
Heating end customer tariff	124,50 €	204,44 €

a. Estimated cost breakdown of the offered heat pump tariff

Concerning power tariff policy, there are large differences between Finland and Germany. In Finland, for building owners with electrical or heat pump heating, approximately 40% of the electrcity price of 120–140 euro/MWh goes to the retailer. The rest consists of network fees and taxes, which is the focus in this work. Therefore, to make comparisons more easily, we used a green power contract with fixed price 52.50 euro/MWh for the energy component in both countries, based on publicly available offers from power providers[15].

In Germany, power is considerably more expensive (280 euro/MWh in 2019) for residential end customers. However, for heat pump customers, there are special heat pump tariffs called "Wärmepumpenstrom" which are clearly cheaper, average 213 euro/MWh[16], and green power offers of 204 euro/MWh were found by the authors. These tariffs have often the requirement that the heat pump must have separate power grid connection, allowing load control by the power provider or DSO during few predefined peak hours each day[17].

Germany has had since year 2000 a progressive feed-in tariff policy for solar and wind power, creating the first real markets for these technologies and provide pioneers and first move industrial players an stimulating development, investment and operation environment. This policy has been funded by the power end customers via a surcharge on top of the network tariff, the so called EEG-surcharge. The EEG-surcharge was below 10 euro/MWh until 2007, but increased to over 60 euro/MWh with the rapid renewable power expansion following the Energiewende after 2013. Today, most new solar and wind project do receive minimal or no feed-in tariffs at all, but the EEG-surcharge has still to fund the pioneering but expensive old installations.

Finland has had a limited feed-in tariff policy, only for a limited amount of wind power installations and no feed-in tariff at all for solar power. The feed-in tariffs are funded from the national budget, so there is no funding required from power tariffs and hence no surcharges to fund feed-in tariffs. Other taxes, levies and the network fees are in total also lower than in Germany, except for the higher 24% VAT. In our calculations, we used the network fees of the DSO [18] responsible for the city of Espoo in Finland.

B. Studied building examples

Two residential buildings located in the city of Espoo, Southern Finland (marked FI in Table III) have been studied in detail and modeled using hourly energy meter readings from smart meters and heating control systems as well as energy audits. In this study, the models made for the Finnish buildings are exploited in generating comparable location specific energy consumption behavior curves and patterns for the buildings in Southern Germany, where the city of Nürnberg was selected as location for the comparison (marked as GER).

TABLE III. STUDIED EXAMPLE BUILDINGS

Building Complex		**Terraced house complex "1975"**		**Apartment building block "2005"**	
Construction year		1974-75		2004-05	
Type		Residential		Residential	
Ownership		Condinium		Rental	
Envelope		Brick, concrete		Brick, concrete	
Floor area, total	m2	4582		9901	
Building volume	m3	15760		31180	
no. of floors		1-2		4	
no. of apartments		29		141	
no. of inhabitants		77		280	
no. of buildings		6		5	
		FI	***GER***	***FI***	***GER***
Heat demand for example year (2018)					
Radiators	MWh	533[b]	379[c]	619[b]	429[c]
DHW end use	MWh	67[b]	67[c]	148[b]	148[c]
DHW circulation	MWh	123[b]	123[c]	236[b]	236[c]
Heat demand total	MWh	723[a]	568[c]	1003[a]	813[c]
Peak heat demand	kW	239[a]	169[c]	325[a]	229[c]
Radiator dimensioning point					
$T_{outdoor}$	°C	-26	*-10* [d]	-26	*-10* [d]
$T_{radiator,supply}$	°C	80	80	70	70
$T_{radiator,supply}$, after heating control update	°C			*55* [e]	*55*
$T_{radiator,return}$	°C	60	60	40	40
Radiator heating activation					
$T_{outdoor}$	°C	18	18	17	17
$T_{radiator}$	°C	23	23	20	20

b. Smart meter measurement.

c. Estimated using smart meter readings.

d. Modeled using GER temperatures and measured heating footprint of FI building.

e. Estimated dimensioning point temperature for GER climate.

f. Original supply temperature was designed to be 70°C at dimensioning point. During an update of the heating control this supply temperature was reduced to 55°C.

The main focus in this study is a Finnish rental apartment building complex, marked with **"2005"** in Table III, consisting of 5 buildings with 4 floors each, altogether a floor area of 9901 m^2 in 141 apartments of size 1–4 rooms+ kitchen+bathroom. This building complex was constructed in 2004-05 according to Finnish building code valid at that time. The building complex has a hydronic central heating system consisting predominantly of radiators. The radiator heating system energy supply is mainly controlled with the supply temperature using the outdoor temperature as input signal for the control curve (see Fig 1). During an update of the heating control system, this supply temperature has been reduced substantially, from 70 °C to 55 °C at the dimensioning point (-26 °C in Southern Finland). Domestic hot water (DHW) is supplied from the same central heating system to the apartments at a supply temperature of $T_{DHW,supply}$ = 58 °C, and a DHW circulation line ensures that the DHW temperature in the apartments immediately above 55 °C when turning on the hot water tap. The same DHW circulation line is used for radiator heating in the bathrooms, ensuring bathroom heating comfort also when the ordinary radiator system is not activated (typically at outdoor temperature above 17 °C). At the same time, these DHW end use and DHW circulation loads provide a heat load that is present also outside the normal heating season.

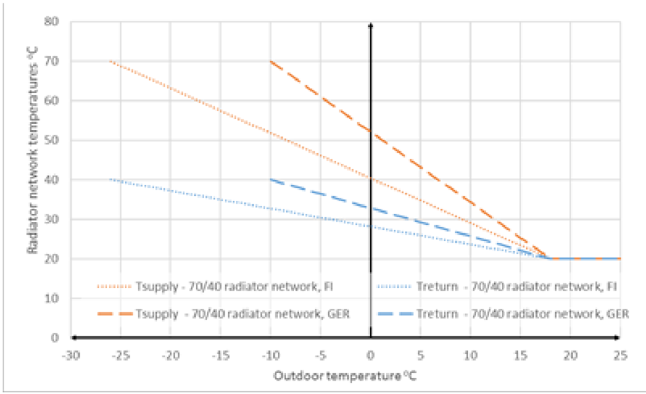

Fig 1 Radiator network control curves (Tradiator,supply, Tradiator,return) approximated for South Finland (FI) and estimated for Southern Germany (GER) for a common 70/40 radiator heating system.

The second building complex in this study, marked with **"1975"**, is a Finnish terraced house complex consisting of 6 buildings with 1–2 floors each, altogether a floor area of 4582 m^2 in 29 larger family apartments of size 4–6 rooms+kitchen+1–2bathrooms+sauna. This building complex was constructed in 1974–75 according to Finnish building code valid at that time. The building complex has also a hydronic central heating system consisting of radiators, but with considerably higher supply temperature of 80 °C at dimensioning point, which is typical for that era. There is also a DHW supply system with DHW circulation, which has approximately same temperature levels as the one in the "2005" building.

Both buildings have their central heating systems supplied with district heating (DH) via a DH substation. At the DH substation, the DH supplier has a smart meter collecting hourly meter readings of the momentary DH energy consumption. Consequently, detailed outdoor temperature dependencies and hour-to-hour patterns of the building heating and DHW consumption behaviour could be modeled as background for this study. These metered consumption dependencies and patterns are in this study used to estimate the heat need for central heated buildings of same construction type, although they were using gas instead of DH. To generalize, it is assumed that the building complex has its own central gas boiler instead of one at the DH substation.

C. Air-to-water heat pump solution and costs

In this study, the focus is on the feasibility of hybrid heat pump / auxiliary heater solutions. The focus of the analysis is on the large building-level air-to-water heat pumps (A2W HP), typically installed for 10-500 kW heating capacity and used to supply heat to centralized hydronic heating systems. air-to-water heat pumps typically do not suffer from installation restrictions, unlike ground-source heat pumps.

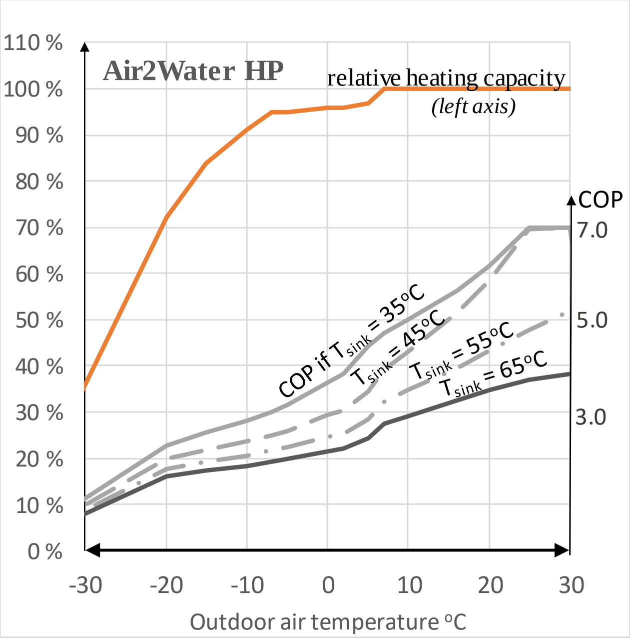

Fig 2 Modeled Air-to-water heat pump characteristics

The coefficient of performance COP, i.e. the ratio of useful heat output to power input, of the air-to-water heat pump is modelled using equation

$$COP = \eta(T_{air}) \cdot \frac{(T_{sink} + 273.15°C)}{T_{sink} - T_{source}}$$

where T_{sink} and T_{source} are the temperatures (in ˚C) of the heat exchanger on the hot (sink) side and cold (source) side, respectively. $\eta(T_{air})$ is a dimensionless degradation factor, describing process imperfections compared to ideal Carnot cycle. For the modeled A2W HP, T_{source} is set in this study to be equal to the air temperature T_{air}. For this model, $\eta(T_{air})$ was then calibrated towards COP data from heat pump manufactures for large 15-80 kW heat pump units[19][20], and reached for this data at best 0.47 at an outdoor temperature range between 7 ˚C and 16 ˚C, while being clearly less at lower or higher outdoor temperatures. Similarly, maximum heating capacity was calibrated in the same way to the manufacturer data. The resulting dependencies of COP and maximum heating capacity on outdoor air temperature are displayed in Fig 2.

For the delivered heat from the A2W HP to the radiator or DHW system, the delivered temperature is set to be 3 ˚C lower than T_{sink}. If this delivered temperature is less than required by radiator or DHW supply temperature, an auxiliary electric heater or gas heater/boiler must supply the remaining temperature lift and heat energy.

Interest free investment costs for the A2W HP are estimated based experience from on projects in Finland, and displayed in table IV.

TABLE IV. HEAT PUMP SPECIFIC INVESTMENT COSTS

A2W Heat Pump Investment estimated costs, large HP	**euro per kW,heat**
HP Unit	300,00 €
Storage Unit	71,00 €
Outdoor Unit	180,00 €
Equipment Cost Total	551,00 €
Installation markup 50%	275,50 €
Total Project Cost	826,50 €

D. Optimization model

For the analysis calculations we use a linear optimization model "SmartP2DH" developed at VTT and dedicated for building level power-to-heat and sector coupling energy analysis. The model is illustrated in Fig. 3 below, and handles building-level heat pump investments and operation in a future smart energy network.

The optimization model includes configurable building heating system characteristics. These include e.g. forecast for the building heating needs depending on the outdoor air temperature adjusted with average heat gains from residents and devices, the ability to handle radiator network supply and return temperature curves which depend on outdoor air temperature (see e.g. Fig. 1), DHW weekly consumption patterns and DHW circulation needs and temperature levels, as well as resident's weekly power consumption patterns.

The model is designed to handle and optimize both operations and energy production investments for a building connected to several grids, i.e. power, gas and/or district heating grid, and the contracts to the energy retailers and grids.

For the power-to-heat and sector coupling analysis, the model has models for gas boiler and district heating operation, as well as submodels for several heat pump technologies including A2W HP, that depend on various heat sources with dynamic temperature behaviour. The model calculates with the optimization both the cost-optimal dimensions of grid connections as well as for each hour the cost-optimal temperature lift, i.e. cost optimal preheating operation, of the given heat pump configuration. The model also calculates the CO2-emissions, including both direct emissions as well as grid emissions.

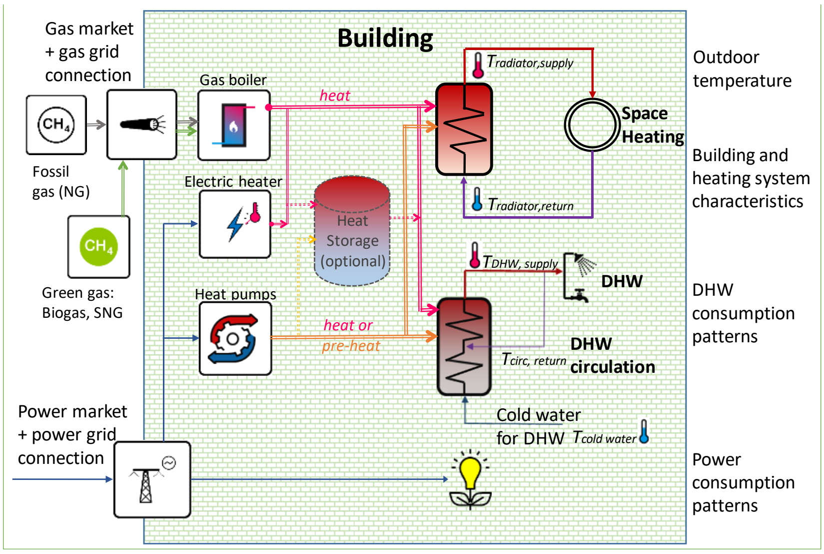

Fig 3 Schematic of the Optimization model

E. *Scenario definitions*

The studied scenarios include combinations of gas tariff scenarios (section II) and different heating systems. The heating system may consist of gas boiler alone (baseline/noHP) or boiler and a cost optimal A2W heat pump (A2WHP). In the latter case, the optimization model results provide the cost optimal A2WHP size for the scenario, typically to a certain part load level of the peak heat demand.These scenarios are calculated for both Finnish (FI) weather and green power tariffs, as well as German (GER) weather and green power tariffs available for heat pump customers. Table V shows the full description of all scenarios.

For the example years studied, we used weather data with hourly time series for the outdoor temperature for one example year. For Finland, we use measurements for the year 2018 from Finnish Meteorological weather station in Tapiola, Espoo, with temperature average 6.8˚C, high 30.2˚C and low -20.8˚C[21]. For Germany, we used the MERRA-2 time series provided by renewables.ninja tool for Langwasser, Nürnberg, with average 10.0˚C, high 33.7˚C and low -8.9˚C[22].

In all scenarios, the interest rate applied by the consumer for financing the investments was assumed to be 3 %. The relatively low discount rate was motivated by the fact that residential building owners can often get long term loans for very low interest rates, today even below 1.5%, as long as the property market is considered at least as stable. Lifetime of air-to-water heat pumps was assumed to be 20 years.

TABLE V. DEFINED SCENARIOS

Scenario definition - Finland	**NG80 Baseline**	**NG80 A2WHP**	**BG90 noHP**	**SNG147 noHP**	**SNG272 noHP**	**Max A2WHP**	**BG90 A2WHP**	**SNG147 A2WHP**	**SNG272 A2WHP**
Fossil or green gas	Fossil	Fossil	Green Biogas	Green SNG	Green SNG		Green Biogas	Green SNG	Green SNG
Gas boiler peak heat demand size	X	X	X	X	X		X	X	X
A2W Heat Pump cost optimal or maximal size		Optimal				Max	Optimal	Optimal	Optimal
Electric heater peak heat demand size						X			
Gas Tariff, eur/MWh	82 €	82 €	90 €	147 €	272 €		90 €	147 €	272 €
Green Power Tariff, eur/MWh	125 €	125 €	125 €	125 €	125 €	125 €	125 €	125 €	125 €
Scenario definition - Germany	**NG57 Baseline**	**NG57 A2WHP**	**BG100 noHP**	**SNG145 noHP**	**SNG264 noHP**	**Max A2WHP**	**BG100 A2WHP**	**SNG145 A2WHP**	**SNG264 A2WHP**
Fossil or green gas	Fossil	Fossil	Green Biogas	Green SNG	Green SNG		Green Biogas	Green SNG	Green SNG
Gas boiler peak heat demand size	X	X	X	X	X		X	X	X
A2W Heat Pump cost optimal or maximal size		Optimal				Max	Optimal	Optimal	Optimal
Electric heater peak heat demand size						X			
Gas Tariff, eur/MWh	56 €	56 €	100 €	145 €	264 €		100 €	145 €	264 €
Green Power Tariff, eur/MWh	204 €	204 €	204 €	204 €	204 €	204 €	204 €	204 €	204 €

III. RESULTS

In this section, we shortly present results for the defined scenarios for gas heating and hybrid heat pump operation, for the example buildings in both Finland and Germany. Our focus is on the example building "2005" with 70/40 heating system, since it can be considered to represent an average case. Results from other two example heating systems give an indication on the sensitivity of the results. Here the "2005" building with 55/40 radiator heating system can be considered to represent the situation of an energy efficient (but not near zero energy) building after a well performed heating system upgrade, while the "1975" building with 80/60 system the typical situation of the old building stock built 30-60 years ago, but not renovated.

A. *Hybrid operation combining heat pump and gas boiler*

The optimization results showed clearly the advantage of a hybrid heat pump heating solution. The heat pump generally operated as base load unit throughout the year, while the gas boiler served generally as peak unit during winter time, as displayed in Fig. 4.

In summertime, the A2W heat pump generally supplied all needed DHW and space heat, reaching on average a COP of 4 in Germany, and reached almost same levels in Finland.

During coldest days in wintertime, the A2W heat pump efficiency decreased because of low outdoor temperature, and operation of the gas boiler became more cost-efficient. To increase the heat pump efficiency and COP, the heat pump performed only pre-heating to 45-52˚C during the cold days, while the gas boiler performed the remaining lift to the required supply temperatures of the radiator system ($T_{radiator,supply}$) and DHW system ($T_{DHW,supply}$), as displayed in Fig. 5. Still, there was only a small decrease in the heating capacity of the A2W heat pump during the coldest day in South Germany, as can be seen in Fig.5. In Finland, the heating capacity of A2W heat pump decreased substantially more because of outdoor temperatures falling below -20˚C.

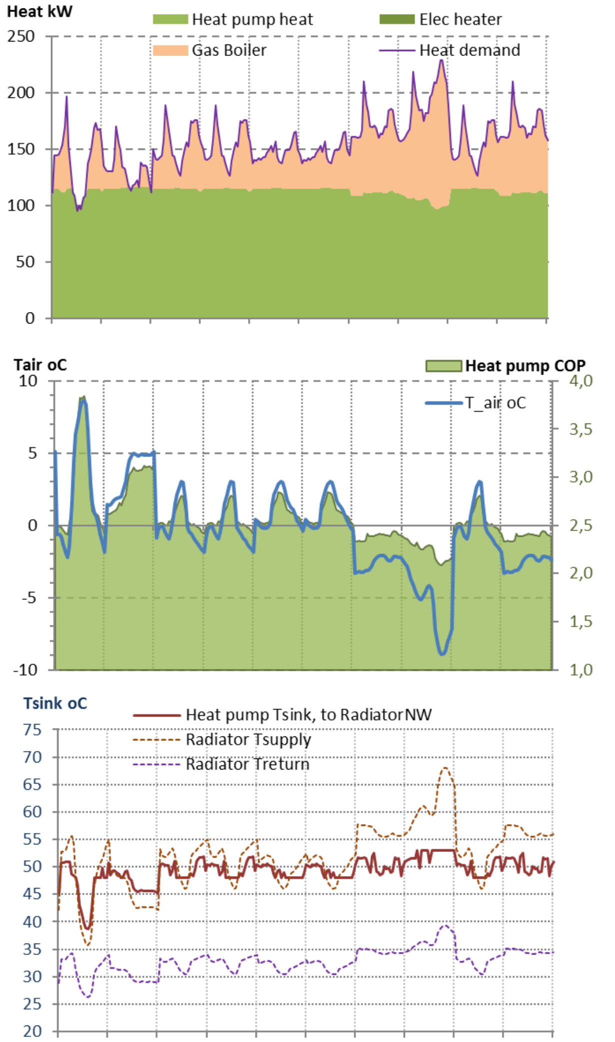

Fig 4 Hourly heat production during last 10 days of the example year. Building "2005" with 70/40 radiator system in Germany, 120kW A2WHP with biogas boiler (Scenario BG100+A2WHP-GER).

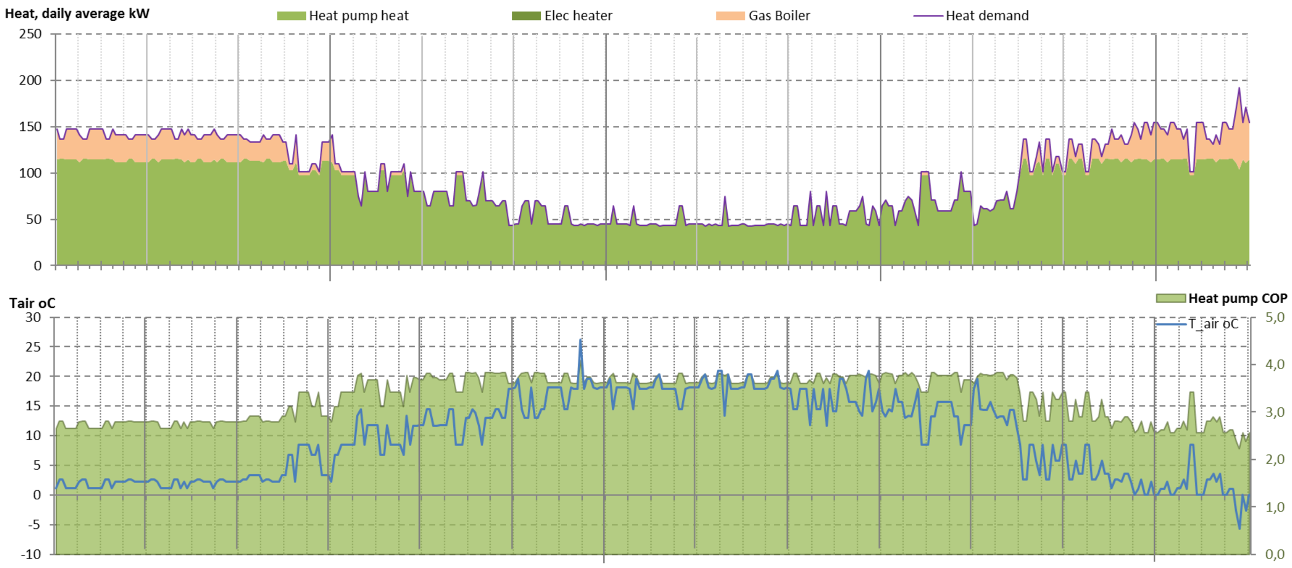

Fig 5 Daily average heat production during the example year, combining biogas and an A2WHP dimensioned to 52% of the peak heat load. Building "2005" with 70/40 radiator system in Germany, 120 kW A2W heat pump (Scenario BG100+A2WHP-GER).

B. *Yearly heating energies, COP, costs and emissions*

For the scenarios, results for yearly heating energies provide by the heat pump and boiler, as well as related costs and CO_2 emissions are displayed in Table VI below.

We can note that with the optimal combination of A2W heat pump and gas boiler, generally a seasonal COP of 3 can be reached. If the tariff policy is in favor for heat pump investments, i.e. the power costs are low enough compared to gas costs, the A2W heat pumps would be sized to 46-74% of the peak heat demand.

Higher (green) gas price would lead to larger heat pump investment. Low fossil NG price, again, combined with high power prices would lead to very small or no heat pump investments at all, preventing sector coupling and cost efficient decentralized green heat production.

The scenarios that favor heat pumps investments show the gas consumption will decrease substantially in those scenarios. For most of the scenarios reducing, yearly gas consumption would be reduced below 12%, and for the SNG scenarios even below 4%, compared to the baseline. This low gas need could practically mean that scarce resources of BG and SNG could maybe be sufficient as peak gas, if a general hybrid heat pump scenario would be promoted by new favorable power and gas tariff policies.

TABLE VI. RESULTS FOR BUILDING "2005" WITH 70/40 RADIATOR HEATING SYSTEM

Results - Finland	**NG80 Baseline**	**NG80 A2WHP**	**BG90 noHP**	**SNG147 noHP**	**SNG272 noHP**	**Max A2WHP**	**BG90 A2WHP**	**SNG147 A2WHP**	**SNG272 A2WHP**
Fossil or Green gas	Fossil	Fossil	Green Biogas	Green SNG	Green SNG		Green Biogas	Green SNG	Green SNG
A2W Heat Pump									
Optimal size, kW heat		150				330	150	210	240
Size, % of peak demand		46 %				102 %	46 %	65 %	74 %
Average utilization, %		68 %				35 %	68 %	53 %	47 %
Average COP		3,00				2,81	3,00	2,87	2,84
Heat demand covered by									
A2W Heat Pump		89 %				99,9 %	89 %	97 %	98,7 %
Electric heater						0,1 %			
Gas Boiler	100 %	11 %	100 %	100 %	100 %		11 %	3 %	1,3 %
Imported Gas, MWh	1179	134	1179	1179	1179	0	134	32	15
Imported Power, MWh	0	296	0	0	0	357	296	340	348
Heating emissions gCO2/kWh, using "grey"grid power	235	60	0	0	0	40	33	38	39
Heating emissions gCO2/kWh, using green power	235	27	0	0	0	0	0	0	0
Heating costs									
Energy, euro/MWh	97 €	47 €	105 €	173 €	319 €	44 €	48 €	46 €	47 €
O&M&I, euro/MWh	0 €	5 €	0 €	0 €	0 €	13 €	5 €	7 €	8 €
Capex, euro/MWh	0 €	9 €	0 €	0 €	0 €	22 €	9 €	12 €	14 €
Heating costs, euro/MWh	97 €	61 €	105 €	173 €	319 €	78 €	62 €	66 €	69 €
Results - Germany	**NG57 Baseline**	**NG57 A2WHP**	**BG100 noHP**	**SNG145 noHP**	**SNG264 noHP**	**Max A2WHP**	**BG100 A2WHP**	**SNG145 A2WHP**	**SNG264 A2WHP**
Fossil or Green gas	Fossil	Fossil	Green Biogas	Green SNG	Green SNG		Green Biogas	Green SNG	Green SNG
A2W Heat Pump									
Optimal size, kW heat		40				230	120	140	160
Size, % of peak demand		17 %				100 %	52 %	61 %	70 %
Average utilization, %		84 %				40 %	70 %	64 %	57 %
Average COP		4,04				3,02	3,17	3,08	3,04
Heat demand covered by									
A2W Heat Pump		36 %				100,0 %	90 %	96 %	98,9 %
Electric heater						0,0 %			
Gas Boiler	100 %	64 %	100 %	100 %	100 %		10 %	4 %	1,1 %
Imported Gas, MWh	956	608	956	956	956	0	94	36	10
Imported Power, MWh	0	73	0	0	0	269	231	254	264
Heating emissions gCO2/kWh, using "grey"grid power	235	189	0	0	0	146	125	137	37
Heating emissions gCO2/kWh, using green power	235	150	0	0	0	0	0	0	0
Heating costs									
Energy, euro/MWh	65 €	60 €	118 €	170 €	310 €	67 €	69 €	70 €	69 €
O&M&I, euro/MWh	0 €	2 €	0 €	0 €	0 €	10 €	5 €	6 €	7 €
Capex, euro/MWh	0 €	3 €	0 €	0 €	0 €	18 €	9 €	10 €	12 €
Heating costs, euro/MWh	65 €	64 €	118 €	170 €	310 €	96 €	83 €	86 €	88 €

C. Differences between building types, impact of radiator heating curve

Figure 6 shows the impact of radiator control curve and the building type on relative heating cost, gas consumption and heat pump utilization in the hybrid gas boiler - heat pump solution. The comparison was made for the German case.

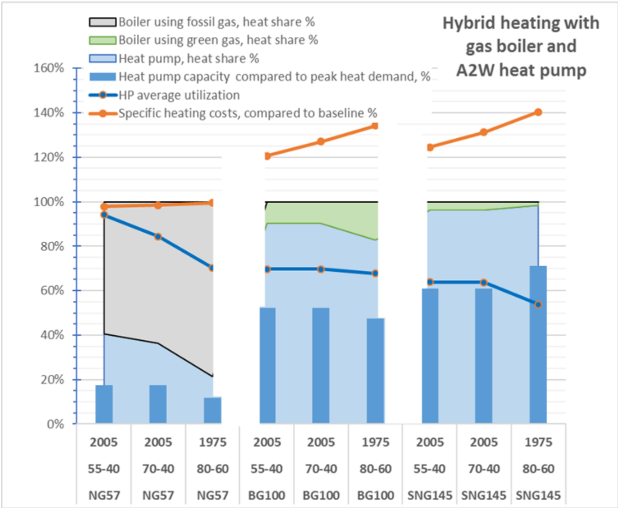

Fig 6 Heat production shares and relative heating costs for different gas price scenarios, building types. The results for radiator control curves with 55 °C supply and 70 °C supply for the "2005" building are also shown.

We see that in the base gas price scenario (NG57) higher temperature radiators lead to higher gas consumption and lower heat pump utilization because of the reduced COP. When gas price increases, the effect disappears.

D. Breakdown of the heating costs

Figures 7 (Finland) and 8 (Germany) show the breakdown of heating costs in the different scenarios.

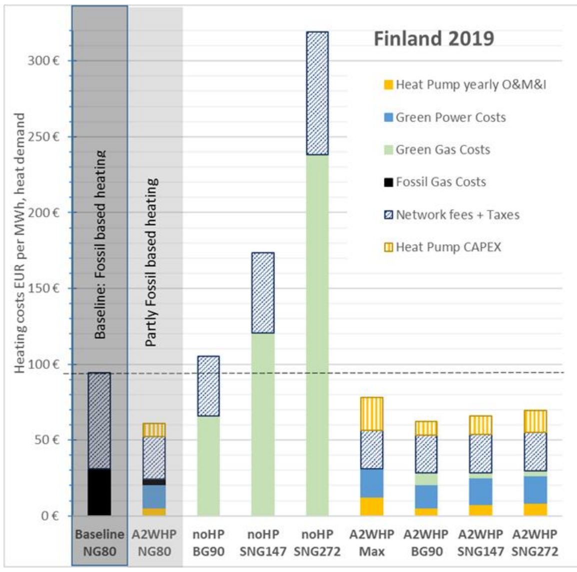

Fig 7 Shares of the heating costs for the appartment building "2005" with 70/40 radiator system, estimated for Finland in 2019.

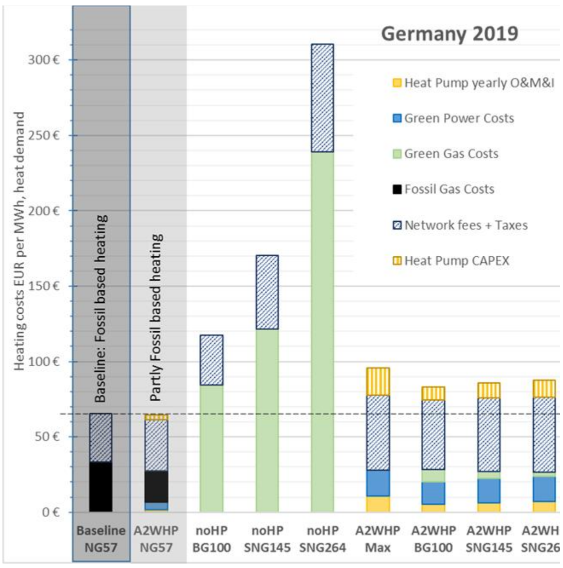

Fig 8 Shares of the heating costs for the appartment building "2005" w. 70/40 radiator system, estimated for Germany in 2019.

In Finland augmenting the gas boiler by A2WHP leads to clear reduction of heating costs and gas consumption. This is true even if gas is substituted by biogas or SNG. In Germany very little cost reduction is obtained although investment into a small heat pump is economically viable. If gas is substituted by biogas or SNG, some increase in heating cost is inevitable but it is held back by installation of a larger heat pump.

In both countries substitution of natural gas by biogas or SNG lead to large heating cost increases.

IV. Discussion

In this section, we shortly discuss the decarbonization potential of the presented heating solutions, the favorable situation in Finland, and present briefly one way to help Germany to improve the heat pump investment climate to enable a cost efficient pathway for building heating decarbonization.

A. *Decarbonization potential of green gas alone*

The analysis showed clearly for both Finland and Germany, that all green gas scenarios i.a. those using biogas or SNG are still too expensive to provide a market based decarbonization of the residential building heating.

Still, green gas can provide an essential component as peak fuel in a decarbonised hybrid heating solution. However, in this case, the green gas consumption has a very small share of the total energy consumption, where as in original scenario fossil gas consumption covered the entire heating energy consumption.

B. *Decarbonization potential of heat pump solution*

For a heat pump to be a real decarbonization solution, green power or low carbon power must be used. Such green power contracts are available in both of the countries at no or only small premium compared to ordinary power contracts.

For Finland, power tariffs and calculation results showed that a heat pump heating solution has already a very significant decarbonization potential. A relatively high fuel tax is levied on natural gas in Finland, and with such tax structures a market based national approach is sufficient enough and no tariff policy changes are needed to enhance heat pump investments. This can be seen in ascending heat pump installation trends in Finland and Sweden.

For Germany, the situation is the opposite. With current German power and gas tariff policies, there is no real market based potential for the heating decarbonization using heat pumps. Fossil natural gas is still relatively cheap, while power is plagued from high grid tariffs, the high EEG-surcharge (whose purpose is to remunerate electricity from renewable energy sources) and other levies like the KWK-Ablage (whose purpose is to remunerate CHP producers), other energy taxes and on top of all these burdens, a 19% value added tax (VAT). Consequently, heat pump investment is not profitable except in very small scale.

C. *Impact of CO2-tax on fossil heating fuels*

To look for alternative tariff solutions that could enhance the German situation, we investigated the impact of a CO_2-tax of 50 euro/tonCO_2 on fossil heating fuels, in addition to the existing taxes listed in Table 1. This tax would have an cost impact of 10 euro/MWh natural gas + VAT19%, total 11.90 euro/MWh natural gas. This would result in Germany in a 21% increase on the resident's heating bill to 69 euro/MWh (still cheaper than in Finland), if no other measures can be taken to reduce the heating bill. However, the gas price increase would not trigger heat pump investments, since the heat pump solutions would still remain more expensive heating solution than fossil natural gas, because of the expensive power network tariffs and heavy power taxation.

An alternative worth to investigate would be to direct the tax incomes from the heating related CO_2-tax directly to reduce components in the heat pump power tariff, like levies and energy taxes like the EEG-surcharge. Since only a fraction of power is needed for the heat pump heating compared to natural gas boilers, i.e. the ratio between the seasonal COP and the boiler efficiency, a multiple effect of the directed CO_2-tax resources can be expected. A CO_2-tax income of 10 euro/MWh natural gas would provide an equivalent potential of a 35 euro/MWh reduction in the EEG surcharge, if a seasonal COP of 3 and boiler efficiency of 0.85 is assumed. The effect of this tax redirection can be seen in Fig. 9 below.

All hybrid gas/heat pump scenarios would reach clear profitability from the end customers point of view, compared to the NG heating with CO_2-tax of 50 euro/tonCO_2. It is especially worth mentioning, that the A2WHP-NG69 scenario would only be slightly more expensive than NG heating without the CO_2-tax, which probably would make such policy socially more acceptable.

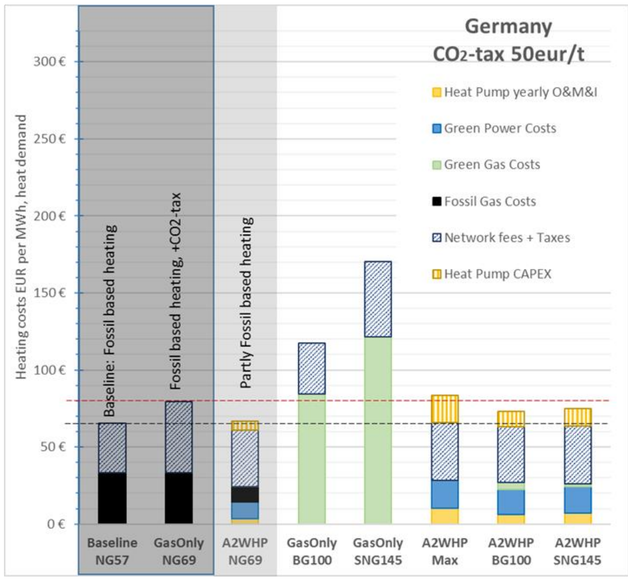

Fig 9 End customer heating costs for the appartment building "2005" with 70/40 radiator system, estimated for a CO2-tax of 50eur/t, redirected to reduce the EEG-surcharge in heat pump power tariffs of Germany

V. Conclusions

The main conclusions that can be drawn from the results are the following. In Finland it is economically sound for the end-customer to augment or replace natural gas heating by an air-to-water heat pump solution, at the same time significantly reducing emissions. However, today direct gas heating is not so common in Finland, since larger buildings in cities are generally connected to the city's DH grid. In Germany, with a very strong position of gas heating, the high surcharges which are placed on green electricity make the heat pump solution economically unattractive. A relatively low fuel tax would change the situation in favor of the heat pump also in Germany. In both countries reducing emissions of gas-heated buildings by substituting fossil natural gas by SNG would significantly increase heating costs.

In future research, it would be necessary to study the effect of increasing penetration of heat pump heating on gas and electricity distribution companies.

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