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Evaluation of combining an air-to-water heat pump with a wood stove with water jacket for residential heating

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Abstract

For decarbonization of the world's energy supply not only power production but also heat generation must switch totally to renewable energies. Heat pumps could be one of the major alternatives for small and medium scale heat utilization. But, power driven heat pumps need electricity especially in winter time, when renewable power from wind and photovoltaics could be scarce. So a backup technology could be helpful. It is shown that a wood stove with water jacket for residential heating can lower peak power demand in winter time significantly. For older houses with radiation heating system the additional wood log stove could be run economical feasible with cheap wood resources.

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Keywords: wood stove combination with heat pump; bioenergy and heat pump; economical feasibility of renewable heating; bi-modal renewable heating

1. Background and Objectives

5th of October 2016 more than 55 states of the world with more than 55 % of global climate gas emissions had ratified the world climate agreement of Paris [1]. One of the major targets is to keep the increase of the average global temperature below 2 °C in comparison to 1850. Additionally, it should be checked, if it could be possible to achieve a limitation to 1.5 °C. That means the global economy should become global warming gas neutral until second half of this century [2].

German policy and funding achieved the commercialization of wind and photovoltaic (PV) power production. At the moment accumulators are one of the most important research topics and massive cost reductions are expected. In 2015 around 7.3 GW of new wind and PV generators were put into operation [3-4]. This is even more than new coal power plants [5]. The transformation of the electricity supply is mostly a question of political willingness, cost efficiency and acceptance of transition processes by the inhabitants. The challenges of such a transformation can be recognized in the heating sector, which showed only a very weak increase in the last years [6-7]. About 10 % of the heat usage worldwide comes from renewables and about 90 % of the renewable heat is supplied by biomass. Slow developments in the heating sector are particularly ridiculous as about 50 % of the global final energy demand is used for heating purposes [7]. Even if 50 % of this demand may

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be reducible by higher efficiency and insulation, there is still a significant amount of heat to be supplied by renewables in the future.

Wherever room heating is of relevance, heat pumps gain installation numbers in comparison to other renewable heating systems. For legislative reasons, as well as for cost reduction power driven air-to-water heat pumps gain in relevance – at least in countries with significant room heating demand like in Germany (see Fig. 1). Since 2010 the number of new installed air-to-water heat pumps is bigger than the number of ground water-to-water systems, with increasing tendency.

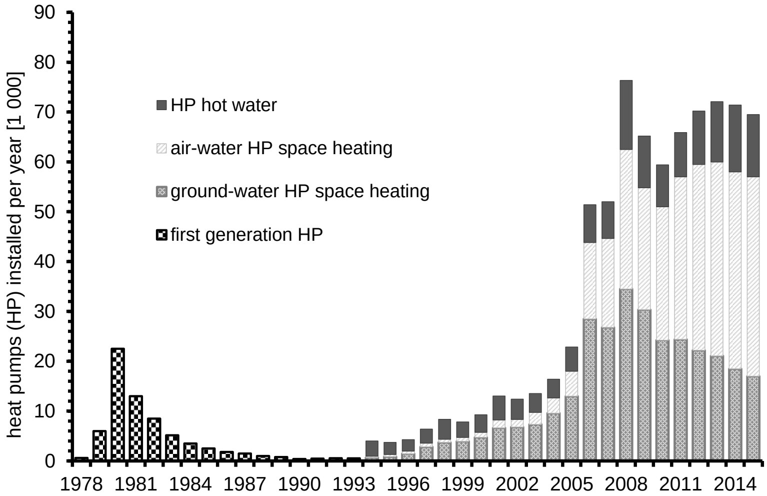

Fig. 1. Development of heat pump installations in Germany – as an example [8]

In general, these systems have two more or less important drawbacks: (i) decreasing efficiency of power to heat dependent on increasing temperature difference between outside and inside – especially with outside temperatures below 5 °C; (ii) increasing power demand during winter time, due to high heating demand and reduced efficiency. That means a high and secure power demand in winter time is needed. But, in winter PV power production is low and wind power generation could also be quite low at least for some days up to weeks. Therefore a renewable energy system could have a power supply problem. This could be solved either by longtime power storage systems, that would probably be quite expensive, or by heat and power generation from storable renewable fuels like biomass or synthetic fuels from renewable power. For individual housing installations another option occurs. Small scale wood log or wood pellet stoves with water jackets could produce cost efficient heat during peak demand time. This opportunity has been investigated and the results are discussed in the following.

2. Method

This study is a very first discussion about opportunities of combining heat generation by power driven heat pumps with a biomass fired heating system. Therefore, one defined case is investigated. Nevertheless, the used methods are set up in a way that they could be used for quite a lot of cases, possible.

2.1. Description of the case and its variations

For the present study two common reference systems for refurbished and for new built single-family houses were defined. The characteristics of the buildings are aligned to the building typology developed by the IWU within the project “Typology Approach for Building Stock Energy Assessment” (IEE Project TABULA) for Germany [9].

The first reference system is an existing building with a usual refurbishment, a floor area of 140 m^2 and an energy requirement of 120 $kWh \cdot m^{-2} \cdot a^{-1}$. For space heating purposes radiator heating systems are used. The second building is a newly built low-energy house with a floor area of 120 m^2 and an energy demand of 30 $kWh \cdot m^{-2} \cdot a^{-1}$. It is equipped with an underfloor heating system. Generic load profiles were created for both systems by adapting measured real load profiles to the defined building characteristics (see Fig. 2). For both buildings a demand of domestic hot water of 1.0 MWh per year is assumed.

Two different heating systems were defined for further evaluation. The basic scenario A1 uses for both buildings a monovalent air-to-water heat pump. The domestic hot water (DHW) is stored in a single water storage with a volume of 150 l. For the improved concept A2 a log-wood stove with water jacket is installed additionally.

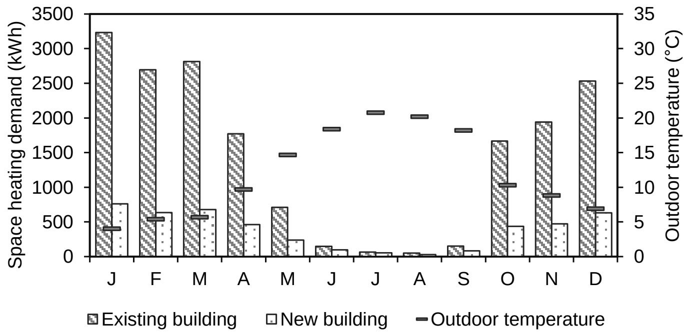

Fig. 2. Monthly demand for space heating and domestic hot water generation of existing building (left columns each) and new building (right columns each) as well as outdoor temperature

The economic evaluation includes effort and costs for the main heat generation with air-to-water heat pump and log-wood stove. Heating manifolds with system distributor, valves and pumps are not considered, the same applies for the domestic hot water storage. The heat distribution system with the water storage for DHW and the space heating circuit as well as optional solar thermal systems and/or ventilation systems are also not considered. Relevant data for both buildings and each of the concept alternatives are given in Table 1. Data is derived from literature, company information and own calculations.

Table 1: Basic data for the investigated building types

		Existing building	New building
Heated floor area	m²	140	120
Space heating demand	$kWh{\cdot}a^{-1}$	16800	3600
Domestic hot water demand	$kWh{\cdot}a^{-1}$	1000	1000
Space heating system	-	radiator heating	underfloor heating
Nominal heat capacity at design point	kW	12.0	3.0
DHW storage	L	150	150
Buffer storage	L	-	300

The final purchasing decision for a log-wood stove is often done either because the wood can be purchased very cheap (e.g. in the own private forest) or the stove is seen as a lifestyle product and is used for the coziness it can provide. For scenario H1 it is therefore assumed that the fuel can be collected for average costs of 15 $EUR{\cdot}MWh^{-1}$ from the private forest (collected, processed and stored by the user). In this case the capital-related costs for the wood stove and the accessory parts will be fully considered. In scenario H2 the stove will be installed because of the cozy ambient of a wood fire and not due to the availability of wood. Therefore the wood has to be purchased from local dealer with a price of 45 $EUR{\cdot}MWh^{-1}$. In contrast to H1 only additional installation costs for the buffer storage and the integration of the water jacket in the buffer are considered here.

In the existing building three logs of approximately 0.9 kg each are used per batch. With a superior calorific value of 4.0 $kWh{\cdot}kg^{-1}$ (water content 20 %) and an utilization rate of 80 % this leads to 8.6 kWh per batch for scenario H1. The superior calorific value of the bought wood in scenario H2 is expected to be higher (4.3 $kWh{\cdot}kg^{-1}$) because of the lower water content of 15 % (see also Table 2). In this case 9.3 kWh are generated per batch in scenario H2. In the new built low-energy building only two logs are used per batch. Using the same wood 5.8 kWh heat is generated per batch in scenario H1 and 6.2 kWh in scenario H2.

Table 2: Basic data for log-wood usage

		Existing building		New building	
scenario of wood usage		H1	H2	H1	H2
superior calorific value	$kWh \cdot kg^{-1}$	4.0	4.3	4.0	4.3
water content	%	20	15	20	15
wood (logs) per batch	kg (-)	2.7 (3)	2.7 (3)	1.8 (2)	1.8 (2)
fuel energy input per batch	kWh	10.8	11.6	7.2	7.8
log-wood price (input)	$EUR \cdot MWh^{-1}$	15	45	15	45

Up to 90 % of the generated heat can be switched to the central heating system, with a loss within the distribution to the buffer of 5 %. The demand for electricity to pump the heat to the buffer is set to 30 W. For the power demand of the heat-pumps a simple correlation between outside temperature and flow temperature is used. The graph of the correlation is shown in Fig. 3.

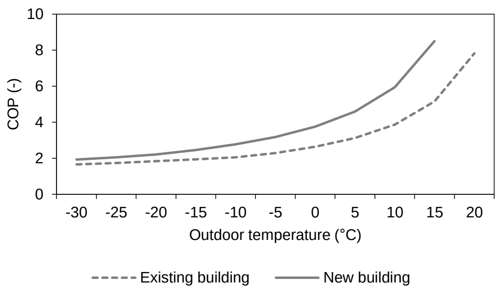

Fig. 3. Simplified coefficient of performance (COP) for both reference buildings according to the outdoor and the flow temperature

2.2. Techno-economic assessment

The techno-economic assessment is done using the annuity procedure of the VDI 2067 Part 1:2012-09 “Economic efficiency of building installations fundamentals and economic calculation”. For the chosen annuity procedure an observation period of 20 years is chosen. The service life of the heating systems is considered to be also 20 years for all systems. The price increase is assumed to be at 2.0 % per year. The only exception is the wood price in the scenario H1, where the fuel is collected from private forests. Here, a price increase of only 1.0 % per year is assumed. An interest rate of 2.5 % is chosen. Subsidies are not considered for the calculation of the capital-related costs. The determination of the annuity of total annual payments is done for gross prices including value added taxes. The investment costs are taken out of list prices without considering trade discounts. The prices for the required electricity are taken from Table 3.

It is expected that the heat pump, the domestic hot water storage, the heat distribution system and all the further components are already installed or have to be installed anyway. These costs are equal for the scenarios and therefore are not calculated.

2.3. Assumptions about the electricity price and the development of renewable energies in power generation

In 2015, 31.6 % of electricity consumption has been covered by renewable energy sources in Germany (Fig. 4).

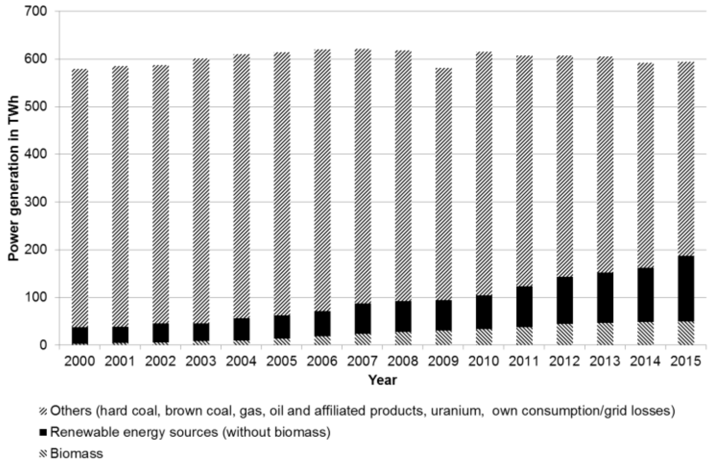

Fig. 4. Power generation in Germany by energy sources from 2000 to 2015 (based on data of [10])

The fluctuation of renewable energies is compensated by conventional power plants, the share of renewable producers (here explicitly biomass) - although generated according to a flexibility bonus - is characterized by basic load operation. Marginal jumps are available at the respective beginning of the month, i.e. only if - according to the regulations - delivery or feed-in contracts can be changed by the plant operators (Fig. 5). Generators and consumers in the low voltage level – as considered in this study for heating pumps – have to contribute to compensate fluctuations only in a very limited way [11-12].

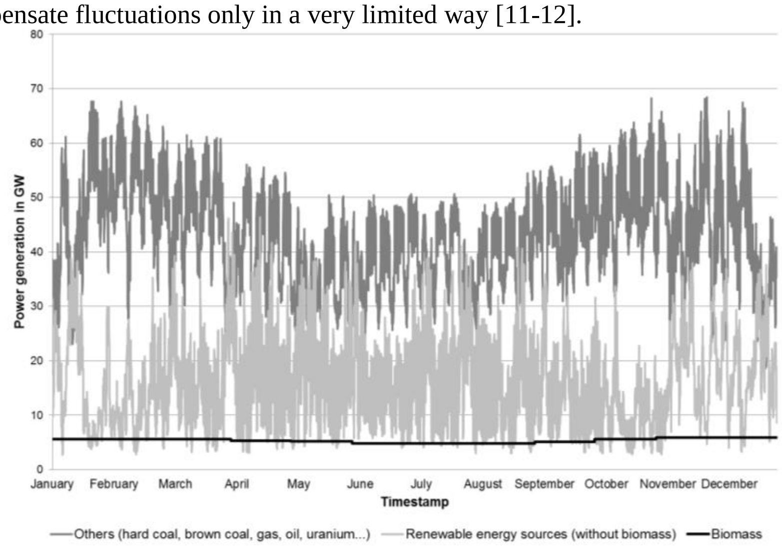

Fig. 5. Power generation in Germany 2015, hourly (based on data of [13])

In contrast to an ordinary household customer (2015: 0.29 EUR·kWh^{-1} [14]), the tariff for heat pump customers is lower. They pay less because a distribution system operator (DSO) has the possibility to switch them off at times. For 2015, we assume an average consumer price for heat pumps of 0.2075 EUR·kWh^{-1} gross [15-16]. Of this, only about 0.0375 EUR·kWh^{-1} gross is the power supply provided by the energy supplier/dealer. About 0.17 EUR·kWh^{-1} gross are made up of additional price components for electricity such as apportionments, charges, grid charges and taxes (Table 3). Currently, the total price is a fixed price for end customers; supply fluctuations have no influence on the electricity price to them. Consumers with heat pump tariffs are billed in the best case according to two time-dependent tariffs. This also applies to cases in which heat pumps connected to the low voltage grid would provide additional services for the grid.

Since 2010, the entire electricity volume which is subsidized according to German Renewables Act (EEG) must be sold at the spot market by law [17]. This procedure makes the purchase cheaper for electricity traders and large customers, but at the same time increases the amount of apportionments under the EEG. The apportionments are inversely proportional dependent on the stock exchange prices, since EEG-subsidies are fixed (dependent on the commissioning year of the installation of a generator). That way supply contracts to final customers also seem to be inflexible and corresponding products are currently missing on the market. The authors of the study [18] assume that a melting-off of these cost apportionments will take place from 2025 onwards (by expiry of the high subsidy of the initial years of the EEG) and the electricity price will rise, but still the sum of stock exchange price and EEG- apportionments will be about at today’s level (scenario P1). From this point onwards, stock exchange price is also likely to have a stronger impact on final consumer prices than it has been the case so far and it is reasonable to expect a new dynamical component within the electricity products. From 2030 onwards, significant supply-side fluctuations in electricity prices are expected [19].

Also important to be mentioned is the fact that there are considerable regional differences for the grid usage charge at distribution grid levels since there is no nationwide grid fee [20]. In a forecast for 2023 we can see a range between less than 0.07 EUR·kWh^{-1} up to more than 0.11 EUR·kWh^{-1}. End users are burdened with higher grid charges if the grid connection point is situated in regions where adaptation actions for the grid were necessary due to the addition of renewable energy producers and if the region is strongly affected by demographic change (scenarios P2a, low fee and P2b, high fee).

Table 3: Additional price components for electricity [21-23] (all values are given in Eurocent·kWh^{-1})

Component	**2015**	**2023, P1**	**2023, P2a**	**2023, P2b**
EEG-apportionment	6.17	6.3	6.3	6.3
CHP-G contribution	0.254	0.438	0.438	0.438
Discharge of electricity-intensive industrial plants (§ 19 StromNEV)	0.237	0.388	0.388	0.388
Electricity tax	2.05	2.05	2.05	2.05
Offshore- apportionment (§ 17f EnWG)	-0.051	-0.028	-0.028	-0.028
Apportionment for switchable loads (§ 18 AbLaV)	0.006	0.006	0.006	0.006
Concession royalty (for special agreements such as heat pumps)	0.11	0.11	0.11	0.11
Average grid usage charge heat pump contract (reduction up to 80 % compared to grid charges for normal end users [22], assumption here: 40 % discount)	3.96	4.62	4.17	6,63
Basic price (grid. measurement. fixed price for power supply†)	1.57	1.57	1.57	1.57
	14.30	15.46	15.00	17.46
VAT (19 %)	2.72	2.94	2.85	3.32
Total	**17.02**	**18.39**	**17.85**	**20.78**
Stock exchange price (informal, gross) on top	3.48	6.90	6.90	6.90

3. Results and Discussion

3.1. Economic advantages for end users

Considering increasing additional price components for the upcoming years, it seems to be possible that a combination of less electricity consumption and avoiding high regional grid fees could generate an economic advantage for end users. The economic advantages that might be achieved by an additional log-wood stove are shown in Fig. 6. Beside the total costs for the log-wood stove also the electricity costs for the standalone use of an air-to-water heat pump are given. For the existing building the stove is working for 693 hours per year. During winter season (between November and March) the stove is typically operated between 18:00 and 22:00. In transition times (September, October, March and April) an operation between 19:00 and 21:00 is given. The stove installed in the new building is running only for 279 hours per year. During winter time (November to Match) the operation is set between 18:00 and 20:00 and during October and March from 19:00 to 20:00. More annual operating hours are hardly to realize. For this the customer has to be willing to operate the stove more than the expected hours per day. This might be possible for transition times in the existing building and the new

† the fixed price for power supply is marginal, approx. 0,05 Ct/kWh calculated on 7.500 kWh·a^{-1}

building. More operating hours lead necessarily to a significantly higher heat input into the living room. This overheating of the installation room also limits the possible operation hours, especially during transition times.

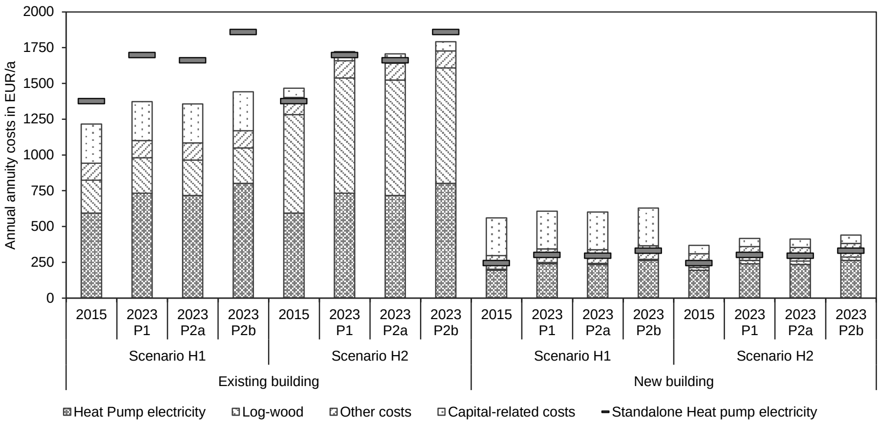

Fig. 6. Annual annuity costs for the described use of the wood stove in the existing and new building within the evaluated scenarios (H1...cheap wood, expensive stove; H2…expensive wood, only additional costs for stove integration; 2015-2023P2b…scenario for foreseen electricity prices according to Table 3)

The results in Fig. 6 show an economic advantage for all scenarios in the existing building using cheap wood. In these cases the log-wood price is low enough to significantly reduce the annual costs. The higher capital-related costs of scenario H1 compared to H2 are also compensated by the lower expenses for wood and electricity. For the lifestyle stove with more expensive wood bought from local trader (scenario H2) an economic advantage can be achieved in the existing building with the electricity price scenario 2012P2b. For the other scenarios H2 lower capital-related costs cannot offset the negative effect of the higher fuel-related costs. Similar results can be seen for fuel scenario H1 and the low-energy building. The low energy demand and the corresponding low fuel-related costs prevent an economic advantage for an additional wood stove. In contrast to the existing building the low-energy building shows better results in fuel scenario H2. Depending on larger increase of electricity prices or even larger variations due to scarcities in electricity supply compared to Table 3 the H2 scenarios could change into economic feasibility.

3.2. Operating times and coefficient of performance

The operation of the wood stove reduces the required operating times of the heat pump by 2375 hours per year in the existing and by 699 hours in the new building (Table 4). These savings increase the coefficient of performance up to 4.14 (+6.9 %; old building) and 5.37 (+2.7 %; new building). The use of the wood stove in combination with a water jacket reduces the heat pump operating time not only by its runtime but also by heat stored in the buffer. While in this study the stove is never operating together with the heat pump the buffer usage is independent of the heat pump state. Table 4 shows that the buffer supports the heat pump 2136 hours (existing building) respectively 532 hours per year (new building). Since heat pumps are interruptible loads, the wood stove provides additional security of supply during peak-load hours.

Table 4: Operating hours of the heat generator and resulting COP (HP…heat pump)

		Existing building	New building
Average heat demand	$kWh \cdot h^{-1}$	3.45	1.12
Heating hours (HP w/o stove)	$h \cdot a^{-1}$	5166	4101
Heating hours (HP with stove)	$h \cdot a^{-1}$	2791	3402
Heating hours (stove)	$h \cdot a^{-1}$	693	279

Heating hours (buffer usage)	$h{\cdot}a^{-1}$	2136	532
COP (w/o stove)	-	3.87	5.23
COP (with stove)	-	4.14	5.37

Intelligent system controllers with weather prognosis could improve the COP of the heat pump even more, by optimizing the use of the stored heat from the stove according to times, where outside temperatures are lowest and heat demand is highest (lower COP of the heat pump).

3.3. Advantages for the national economy

Each kWh of electricity from coal replaced avoids between 6 and 8 Eurocent external costs [21]. Additionally, the reduction of peak load and peak-load supply can reduce the necessary network and system security actions of network operators (redispatch, use of reserve power plants, feed-in management) in accordance with §13 EnWG [24] and related costs. The cost estimation for these actions in Germany is about 0.04 $EUR{\cdot}kWh^{-1}$ for the year 2015 [22]. In addition, there is the need for grid expansion through the increase of decentralized generators in voltage levels and subnetworks, which are "historically determined for comparatively low load flows" and much of the need for reinforcement can be found in rural areas [25]. This entails grid expansion costs. In the low and medium voltage levels they are triggered by a lack of transport or distribution capacities. Criteria for equipment overload, voltage ranges and power-related conditions for the connection of decentralized generators might become violated. The local reduction of peak load and peak-load supply can reduce the necessity for grid expansion, too. The authors of [26] quantify investments to be avoided in feed-in points of rural areas of around 70 $EUR{\cdot}kW^{-1}$ (for systems up to 30 kW), if load and feed-in management by intelligent measuring systems is performed. We would also include this in the case of a combination of heat pump and woodstove with water jacket. The performance range considered in this study is set for a single-family house with a maximum of 30 kW.

Results from further research suggest a potential for flexible heat pump operation, which can reduce residual peak loads by up to 4 GW [27]. Currently, in Germany there are a three backup systems outside the electricity markets that are able to meet peak demand requirements: (i) additional redispatch potential in winter (Grid reserve, §13d EnWG and NetzResV), (ii) (fossil) capacity reserve if German electricity markets (existing contracts, stock exchange, control reserve) are not capable to cover the electricity demand (§13e EnWG and draft KapResV) and (iii) a safety precaution of lignite coal power plants (§13g EnWG). In case (i) there have been estimated costs of 122 Mio EUR for a grid reserve in 2015/2016 [28] and a reserve power of 6.7 to 7.8 GW [29]. That would mean expenses of around 17 $EUR{\cdot}kW^{-1}{\cdot}a^{-1}$ in cause of bottlenecks in transport capacities. In case (ii) costs between 50 and 100 Mio $EUR{\cdot}a^{-1}$ are estimated from 2017 onwards for around 2 GW [23]. Here expenses between 25 and 50 $EUR{\cdot}kW^{-1}{\cdot}a^{-1}$ are expected in case of bottlenecks in power supply. The costs of lignite coal or fossil energy sources respectively as mentioned in (i) and (ii) are those costs on top of the grid charges which could be partly avoided.

Taking an average cost potential of 40 $EUR{\cdot}kW^{-1}{\cdot}a^{-1}$ in consideration the log-wood stove could avoid about 240 EUR per year of net costs for the old building (COP 2) and about 40 EUR for the new one, respectively (COP 3). This advantage could partly be used for a special subsidy, giving part of the advantage to the customers, improving the economic advantage of the combination with a log-wood stove.

4. Conclusion and Outlook

Heat pumps using renewable electricity are one of the promising renewable heating technologies of the future. Main disadvantage may be the high electricity demand during very cold phases of the year with occasionally low renewable power generation. During these time slots, either power from coal, oil or gas plants has to be used, or consumers have to stay in a cold housing or, e.g., a log-wood backup stove compensates the lack of renewable heat.

Economic and electricity supply aspects were discussed. As a consequence it was seen that supplemental use of a log-wood stove might be a useful. For buildings equipped with high temperature heating systems the economic advantage has been shown. With the assumed frame conditions an additional log-wood stove gains mostly advantages if a cheap wood fuel is used. A lifestyle stove with expensive fuel seems to result in higher annual costs and no economic feasibility even not considering the investment costs of the stove itself. For new buildings with low temperature heating systems the electricity saving potential seems to be not high enough for an additional heat generator. In this case with low heating demand the lifestyle stove with more expensive wood fuels is much nearer to economic feasibility. Considering the general advantage of grid stabilization by the use of the stove, a subsidy from these system savings could turn the picture.

Despite today's view on the concept comparison, some major changes will occur in the future. Following the Paris goals, until 2050 the energy supply system of the industrialized countries has to be switched towards a more or less fully renewable energy supply. That means there are only minor differences according to CO_{2eq} between the different scenarios. Besides, power utilization in times of low PV and wind supply will become quite expensive. With biomass prices at the same value of today, price for heat from heat pumps in winter time could arise, so that even in buildings with low heat demand the back-up stove could become economical feasible.

Independent from the individual situation of the customers, it has been shown, that the additional integration of a log-wood stove with water jackets into an air-to-water heat pump system for house heating is favorable for a general renewable energy supply system. Even a well operated log-wood stove could reduce electricity demand peaks and generate significant cost savings in the system of some hundred EUR per year per individual housing.

To improve the easiness of operation and to gain full effect on net stabilization either a pellet stove with automatic control by the house heating system or an improved log-wood stove with automatic starting option and control have to be developed and considered in the calculation.

For heating grids and apartment buildings comparable hybrid systems could be considered consisting out of a heat pump and a micro-CHP system for solid biofuels. In this case not only the electricity demand reduction during time slots with low renewable electricity generation can be assessed, but also the electricity generation from the micro-CHP.

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