2022

Potential of Power and Heat Prosumers for Climate-Neutral Energy Systems

Benedikt Gregor Bederna

Riley Bradley Barta

Bederna, Benedikt Gregor and Barta, Riley Bradley, "Potential of Power and Heat Prosumers for Climate-Neutral Energy Systems" (2022). *International Refrigeration and Air Conditioning Conference.* Paper 2404.
https://docs.lib.purdue.edu/iracc/2404

Potential of Power and Heat Prosumers for Climate-Neutral Energy Systems

Benedikt G. BEDERNA[1]*, Riley B. BARTA[1]

[1] Technische Universität Dresden,
Bitzer-Professur für Kälte-, Kryo- und Kompressorentechnik,
01062 Dresden, Deutschland
benedikt.bederna@tu-dresden.de

* Corresponding Author

ABSTRACT

The political and social aims of a climate-neutral transformation of the energy industry are inextricably linked by the need for a massive extension of renewable electric power generation capacity. Beyond this indisputable point, the question arises in which way the energy demand can be covered during periods without sufficient renewable energy generation. Various approaches to address this question are still being discussed. According to the current political commitments in the US and in Germany, this question is answered differently. While on one side the continued use of fossil fuels in combination with CO_2 storage is seen as a solution, the other side relies on short-term electricity storage and synthetic fuels for long-term storage. Cogeneration, which has been propagated in recent decades, must be reconsidered from this point of view. Currently, the integration of a heat pump (HP) into the previously Combined Heating and Power (CHP)-fed heating networks for covering the heat demand in times of regenerative surplus is particularly obvious in order to reduce the consumption of fossil fuels and CO_2 emissions. Instead of a HP, this publication proposes further integration of a reversible heat pump Organic Rankine Cycle (ORC) unit, creating a prosumer. In this context, "Power and Heat Prosumer" stands for a power plant network optimized for bi-directional power-driven operation coupled with a heating network. It can provide heat for the network using renewable electricity or electricity during periods of renewable electricity shortage. The ORC operating mode thus increases flexibility and conversion efficiency of the plant network. The enhancement of a HP to a reversible system is comparatively simple for scroll and screw compressors up to the single-digit MW range through the integration of a working fluid pump as well as slight adaptations to both the low-temperature heat exchanger and the peripheral equipment. The application potential of a Power and Heat Prosumer is illustrated by a case study of a typical 2 MW local heating network. With study data for the year 2045, the usefulness of the ORC operating mode can be validated. The overall economic goal of the prosumer, however, is to reduce the necessary addition of conventional peak load generation capacity needed during periods of renewable electricity shortage. The maximum reduction potential consists of the capacity of installed reversible HPs multiplied by the ORC efficiency. In combination with a thermal storage, this results in the additional functionality of a Carnot battery, which can reduce the needed short-term storage capacity by the same amount.

1. INTRODUCTION

In recent years, an increasing number of economies and private sector companies have committed to becoming carbon neutral (net-zero) (Learson et al., 2020, IEA, 2021). The key mechanism for accomplishing this goal is a large-scale addition of renewable generation capacity. Unlike conventional generation, these sources are not regulatable. This results in a permanent difference between the current renewable electrical energy supply and the actual grid load. The value of the total load minus the renewable generation is called the residual load. A positive value means a lack of renewable power, which must be supplied by conventional power plants or energy storage systems. If there is a strong increase in renewable generation, the hours of negative residual load will rise. Figure 1 illustrates this situation by an arranged annual duration curve. Thereby, it contrasts the situation in which renewable generation only takes a supplementary share (today) with the situation of an energy industry based mainly on renewable sources. Since the grid must always be physically balanced, either additional consumers must be connected, or generation capacity must be curtailed in the event of negative residual load. However, a curtailment of wind or solar power always corresponds to an economic loss since this electricity has already been financed by the installation of the plant. More difficult than dealing with a negative residual load is meeting the demand during periods of a regenerative power lack. For this situation, either the generation side or the consumer side can be adjusted. As in the existing fossil energy system, the difference could be covered by conventional thermal power plants. However, to keep them emission-free, either synthetic fuels have to be used or the CO_2 in the exhaust gas must be captured and stored, a technology which will be herein referred to as Carbon Capture and Storage (CCS).

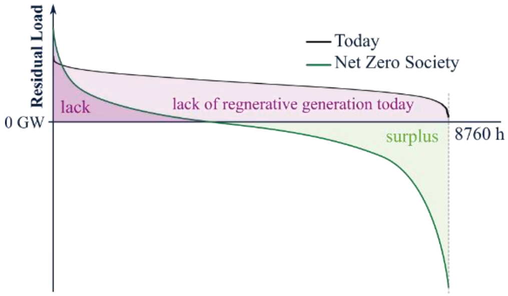

Figure 1: Sketch of the arranged annual duration curve of the residual load and identification of lack and surplus of regenerative power generation

In addition to conventional power plants, storage facilities (battery, pumped or thermal electricity storage) can also increase the generation. Furthermore, it is also possible to adjust the consumption. This approach, known as demand side management (DSM) relies on temporal load shifting, especially through storage systems at the utility energy level and sector coupling. The disadvantage from an economic and resource point of view of both approaches is that a large number of plants (power plants or storage facilities) have to be installed and maintained, even though they have only limited full load hours. In contrast, the total non-renewable plant and storage capacity needed could be reduced if the rigid boundary between electrical consumers and generators is removed and a power unit is enabled to be a consumer as well as a producer (prosumer). The optimal situation would be a unit that receives electricity in times of renewable surplus and feeds in electricity to strengthen the grid in times of electricity shortage. Regarding heating and cooling applications, such a system is quite realistic, because thermodynamic cycle processes can generally convert heat into work and work into heat. The system would therefore be a heat pump (HP) that changes its thermodynamic sense and converts an external heat source into electricity by an Organic Rankine Cycle process (ORC) in times of lacking electricity. The application possibilities of such a combination of both functions in one system have already been investigated in the past by Dumont and Lemort (2019). The aim was to identify use cases where the temperature levels, the waste heat and the heat or cold loads are favorable for both types of processes. Furthermore, work has been carried out in recent years on the technical feasibility. Regarding reversible scroll machines, the experiments of Dumont et al. (2015 and 2021) and recent work by Charalampidis et al. (2021) can be mentioned. There is ongoing work on the topic of reversible screw machines by Steger et al. (2021). Frequently, the Carnot battery (see Dumont et al. 2020) is referred to as an application for such a reversible system. Its idea is either the electrical support of regeneratively fed grids. This publication expands this idea to the full scale of the electricity production and proposes the combination of a reversible HP-ORC unit with a Combined Heat and Power plant (CHP) as a possibility to minimize the conventional power generation capacity in climate-neutral societies. This combination shall be called Power and Heat Prosumer, which means a power plant network with heat supply that is optimized for a bidirectional power-driven operation mode. It can receive electricity from or feed it into the grid, depending on the residual load, and at the same time meet the required heat demand of a heating network. Initially, the future application potential of CHP plants in climate-neutral economies is critically analyzed and afterwards the possibilities of a technical realization is identified. Finally, the operating characteristics in the year 2045 of this prosumer are examined using a typical German use case.

2. POTENTIALS OF CHP PLANTS IN NET ZERO STRATEGIES

2.1 Contemporary Challenges of the CHP Technology

Cogeneration has long been considered an important technology for reducing CO_2 emissions in the power sector and increasing energy efficiency. It has also been promoted as a means of limiting the need for new transmission infrastructure and reducing costs of electricity (IEA, 2008). However, two aspects currently challenge its use. On the one hand, CO_2 emissions should no longer only be reduced, but rather driven to net zero, and on the other hand, the dependence on imports of fossil fuels, especially in Europe, leads to limited room for political action. Both difficulties apply to all CHP plants that run on fossil fuels. Another emerging trend also challenges the current value of CHP plants. In an electricity mix with a high share of renewables, flexibility of generation is becoming increasingly important compared to efficiency. Until now, CHP plants have been designed, especially with small capacities, to achieve high full load hours and high overall efficiency. However, if renewable electricity is available during times of heat demand, the operation of the CHP plant becomes inappropriate due to the additional CO_2 emissions. An alternative would be synthetic fuels, but these require complex conversion processes from regenerative electricity, resulting in significant energy losses. Therefore, during a renewable energy surplus, the use of a HP is a better solution for covering the heat demand. The implementation of HPs in existing grids will therefore become more and more important[1]. That is why the operating hours of CHP plants will continue to decline with the increasing expansion of renewable generation. With regard to climate-neutral energy supply, the fundamental question arises whether it still makes sense to use non-biomass fired CHP plants. This assessment highly depends on the national climate neutrality strategies. The importance of district and local heating networks is not affected by this. For Germany, studies assume that the importance of thermal networks will grow in advancing energy transition (Sterchele et al., 2020).

2.2 Comparison of Pathways to Net-Zero

Climate-neutral power generation can be achieved in different ways. Basically, a distinction can be made between strategies that completely avoid the use of fossil fuels and those that still use them. In this section, the difference between these two approaches will be illustrated using the U.S. and the German strategies (figure 2). The figure on the left is the "US long-term strategy" of November 2021 (US, 2021), which aims to achieve climate neutrality in 2050. It includes a major expansion of renewable energy, a slight expansion of nuclear power, and the addition of the CCS technology to much of the conventional power plants. Non-fossil fuels, such as hydrogen and methane, take only a small share on electricity generation. Despite the large renewable capacity built up, the conventional power plants are needed to cover the periods of a positive residual load. The advantage of this strategy is that the existing generation and distribution infrastructure can still be used. For this reason, the IEA also foresees CCS in power generation in its studies (IEA, 2021). For gas networks, this means that natural gas is still transported and only a share of hydrogen or methane will be added (Larson et al., 2020). In contrast, the German scenario does not use CCS shown by the figure on the right. This figure is a representation that was built up by the authors and is based on the different scenarios of a study by the Fraunhofer Institute ISE (Brandes et al., 2021), which was developed for the political target of climate neutrality by 2045. Also on a European level, the importance of CCS has been decreasing for some years and is currently only considered for the industrial sector (EU, 2021). In times of positive residual load, the electrical energy is instead provided by storage systems and conventional plants burning synthetic fuels. However, the needed capacity according to Brandes et al. is 241 GWh of storage and 152 GW of plant capacity. This is quite high considering that the current installed storage and conventional power plant capacity in Germany is 45 GWh and 84 GW. The synfuels are to be produced with renewable surplus energy in electrolysers and methanation plants as well as imported. How the existing infrastructure must be converted for this purpose is currently the subject of complex discussions.

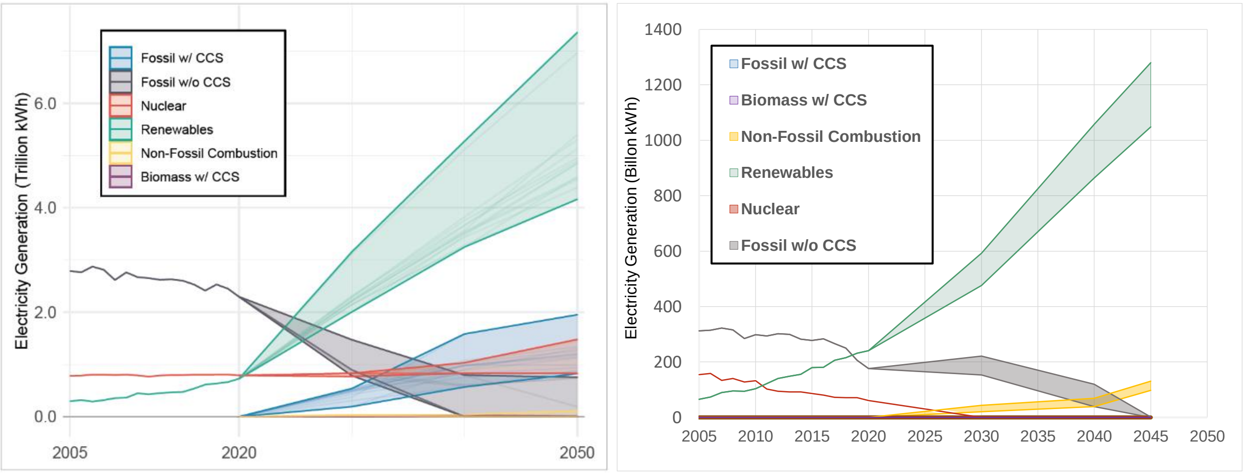

Figure 2: Comparison of pathways to net-zero emissions: US long-term strategy (US, 2021) (left) and a representation of different scenarios (Brandes et al., 2021)[2] fulfilling the German net-zero pledges (right)[3]

---

[1] This trend can already be seen today in the special subsidies newly introduced in Germany for so-called "iKWKs". These CHP plants also have a regenerative heat input (Briem et al., 2020).

[2] To determine the share of non-fossil combustion, the supply of gases was evaluated. The data up to 2020 was taken from energy-charts.info.

[3] An additional specific German political goal is the parallel withdrawal from nuclear power.

2.3 Potential of Decentralized Combined Heat and Power Plants

For currently natural gas-fired CHP plants, the scenarios result in different perspectives. Whereas in the U.S. approach, CO_2-containing fuel as natural gas is still present at the existing gas connection, in the German strategy, this can be considered to be a synfuel and thus CO_2-neutral. Consequently, in the first approach, the CHP plant itself has the responsibility for CO_2 neutrality, which is only realizable by the capture of CO_2. However, since the capture of CO_2 in combustion processes involves a large technical effort (Raza, 2019), this is unlikely to be economically or technically viable for small decentralized power plants. Consequently, its future use is in question. In Europe and Germany, otherwise, there will be the possibility of using CHP systems in local heating networks further on. Nevertheless, the base load will likely be provided by HPs. The CHP plants will be power-driven and run only as a peak load power plant at positive residual load.

3. TECHNICAL REALIZATION OF A POWER AND HEAT PROSUMER

The promoted combination of a CHP plant and a HP can already be understood as a heat power prosumer. Anyhow, the power driven operation of the CHP plant has the disadvantage that heat utilization is not assured and thus the overall efficiency can become rather low. Nevertheless, if the HP is designed as a reversible system, the electric efficiency can be increased by waste heat recovery.

3.1 Reversible Heat Pump-ORC Unit

In order to convert a HP to a reversible system, only one working fluid pump has to be added in the cycle in parallel to the expansion device. Furthermore, additional pumps could be necessary to inverse the direction of the external flows. Edge-controlled displacement machines are particularly suitable for a reversible compressor-expander machine, since the operating principle can be adopted directly here. Only the direction of rotation has to be reversed. To ensure lubrication in these machines, there is normally an oil separator in the high-pressure steam line, as in HPs. Unlike in HPs, this means that the oil circulates in the circuit. Therefore, the compressor motor can simply be reversed to operate as an generator, but the power electronics must be designed with feedback capability. For large reversible plants in the two-digit MW range, turbomachinery is the only option. However, for turbomachine applications it makes sense to use individually optimized compressors and expanders in parallel rather than reversible machines.

3.2 Hydraulic Integration

There are several options for integrating the reversible unit into a CHP-fed heat network (figure 3). For HP operation, an additional pump is required, which allows parallel flow from the return pipe through the condenser into the flow pipe. For ORC operation, a parallel connection is also possible, whereby the hot water must be cooled down from the flow to the return temperature. In the event of a heat surplus due to full load of the CHP plant, the evaporator could also be connected in series, increasing the average temperature of heat absorption and thus the thermal efficiency of the ORC process. This is particularly useful in heat networks where the amount of heat transferred is controlled by the height of the feed temperature. However, in the case of full heat conversion to electricity (no heat load), a parallel circuit is necessary. Consequently, a flexible interconnection could also be implemented.

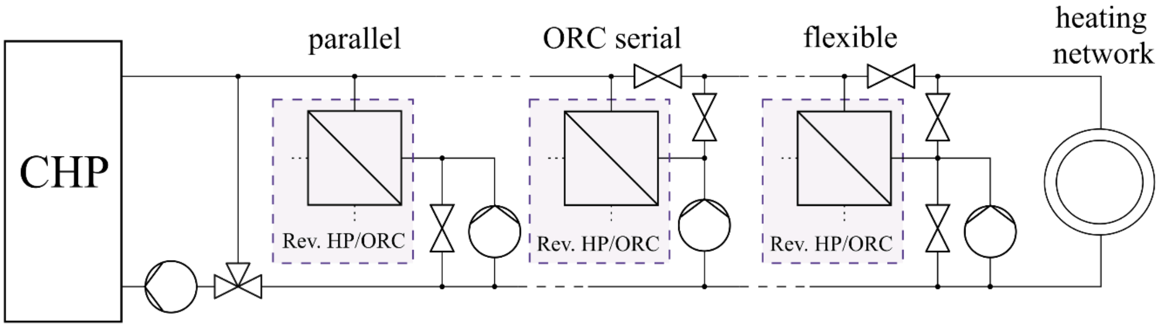

Figure 3: Possibilities to integrate the high temperature heat exchanger of reversible HP-ORC units in heating grids

Furthermore, it has to be prevented that cold water is fed into the flow pipe at the beginning of the HP operation. For this purpose a recirculation loop must be included. When starting up an ORC process the fluid leaving the evaporator may under- or exceed the temperature of the return pipe. However, these cases can be handled by the CHP plant temperature control system. If the temperature is too high, the volume flow rate would be reduced. Otherwise, if the temperature is too low, hot water is mixed in via the bypass. In the long term, the return temperature after the ORC must not be too high, since the cooling of e.g. a motor CHP systems has to be ensured. The additional integration of a heat storage system in the grid would enable not only an effective DSM in which the heat is stored at times of electricity surplus, but also the reconversion of heat into electricity. The heat does not necessarily need to have been previously provided by the HP (Carnot Battery). It would also be possible, to convert solar heat at night in summer.

3.3 Operating Conditions

The different interconnections enable different operating modes (table 1). These depend on the residual load, the feed-in demand, the heat load and the size of the HP and CHP plant. Feed-in is considered to be necessary, if fuel consuming peak load capacity (e.g. gas turbine, combined power plants) would be needed to stabilize the grid. According to Brandes et al. (2021), this condition occurs particularly often in winter months. In addition to the monovalent operating states (HP and CHP) and the envisioned waste heat recovery (CHP+ORC), two undesirable states occur. HP+CHP means that despite the presence of a renewable energy surplus, the CHP plant has to run on synthetic fuels due to a high heat load. This can be avoided by a sufficiently large dimensioning of the HP. If the heat load exceeds the CHP capacity in times of positive residual load, instead, the HP must also be put in operation. This is not desirable, since less electricity can then be fed into the grid despite the high demand. Nevertheless, such cases are quite conceivable, since current CHP plants have often only been designed for base load operation. Thus, a peak load boiler takes over the remaining power.

Table 1: Operating conditions of the power and heat prosumer

Residual load < 0		Residual load > 0			
		Feed-in not required		Feed-in required	
$\dot{Q}_{load} < \dot{Q}_{HP,max}$	$\dot{Q}_{load} > \dot{Q}_{HP,max}$	$\dot{Q}_{load} < \dot{Q}_{CHP,max}$	$\dot{Q}_{load} > \dot{Q}_{CHP,max}$	$\dot{Q}_{load} < \dot{Q}_{CHP,max}$	$\dot{Q}_{load} > \dot{Q}_{CHP,max}$
HP	HP+CHP	CHP	CHP+HP	CHP+ORC	CHP+HP

In summer, HP operation is expected to dominate. When a positive residual load occurs, the CHP will provide the heat. A feed-in requirement is not expected, since short-term storage (battery, pumped storage) can close the generation gap. However, this also sidesteps unfavorable condensing conditions of the ORC process. Due to the feed-in demand in winter, the CHP plant full-load operation is increasingly needed in these months and the CHP+HP mode will also occur regularly. In moderate climates, transitional periods are of particular interest. Here, the HP, CHP and CHP+ORC modes are mainly to be expected.

3.4 Potential Applications in the Future

Regarding the application potential of prosumers, a distinction must be made between centralized large-scale CHP plants on district heating networks, which can be upgraded with the CCS technology, and decentralized small-scale plants (motor CHP, small gas turbine) on local heating networks. Globally, large-scale CHP plants can be supplemented with reversible plants at the site itself or decentral anywhere in the heating networks. These places can be selected due to the availability of lucrative heat sources as surface water, wastewater, waste heat, etc. Decentralized units are probably of smaller size, which would allow the use of positive displacement machines. For the addition of local CHP-fed heating networks, as the European strategy allows, the triple-digit kW to single-digit MW range is equally suitable. For smaller capacity, however, the specific costs increase and on the other hand, the importance of small CHP plants in the building sector is considered to be low according to Brandes et al. (2021).

4. CASE STUDY OF A DISTRICT HEATING NETWORK

4.1 Scenario

The long-term potential of decentralized CHP plants in Germany will now be examined using a case study. For this purpose, a typical local heating network in Dresden supplying a residential area in the year 2045 will be considered. It is assumed that the network exists already today and is fed by a motor CHP unit of 1,000 kW heating capacity. For peak load coverage, a natural gas burner with 1,000 kW_{th} is present. The aim is to decarbonize this network by the addition of a reversible HP-ORC unit. For the year 2045, it is assumed that 100% synthetic fuel will be provided by the existing grid connection. However, this is expensive, and its use should be avoided. It is of secondary importance whether it is methane or hydrogen, because hydrogen capability is assumed (Jennbacher, 2022). Since it is expected that high heating loads will occur during times of high electricity demand, the added HP is not designed for the total heating capacity, but only for 1,000 kW. A geothermal well field and an ambient air heat exchanger serve as renewable heat sources. In addition, in the case of CHP operation, its waste heat, e.g. from charge air cooling and exhaust gas condensation, can also be coupled in (Braasch et al., 2017). The flow temperature of the heat network is constant at 90 °C and the return temperature at 70 °C. A flow diagram of the system is shown in figure 4.

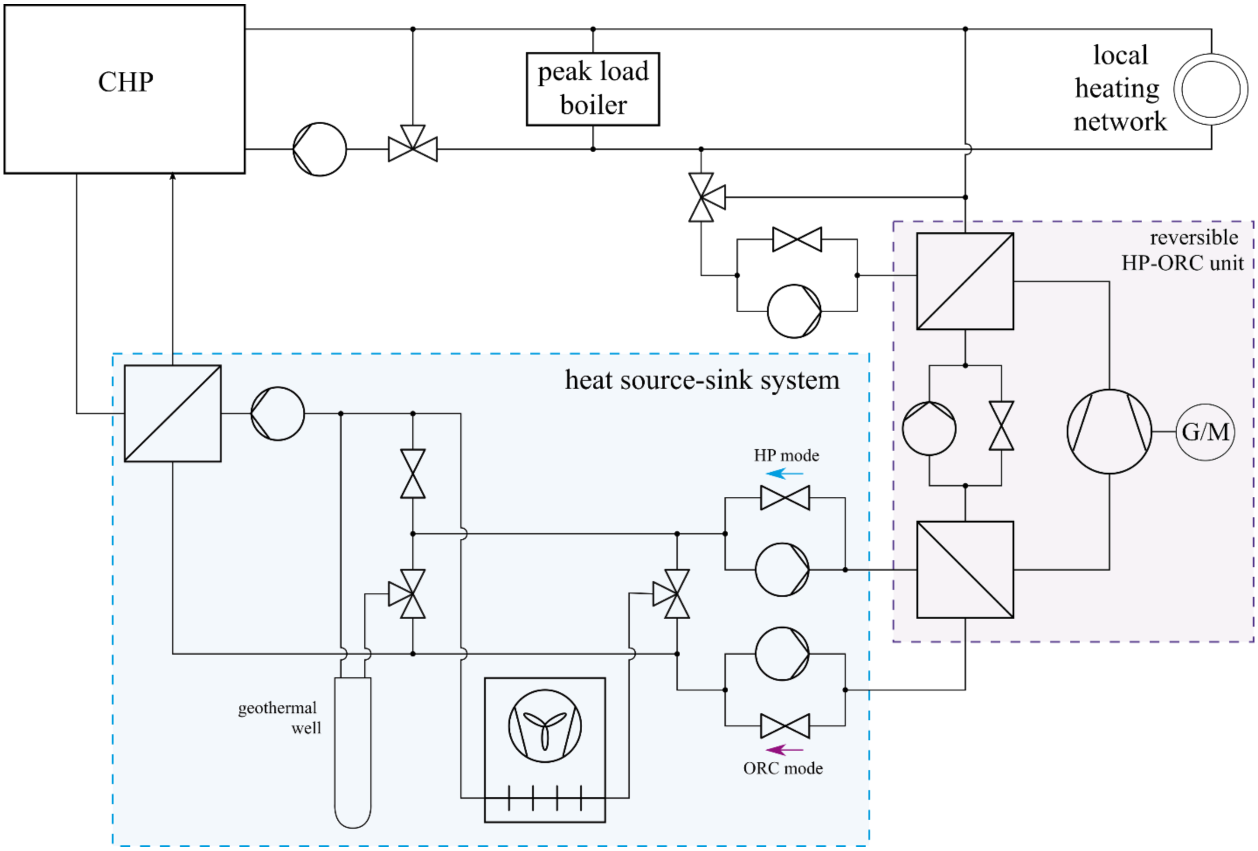

Figure 4: P&ID of the power and heat prosumer and the source-sink system integrated in a local heating network

4.2 Theoretical Technical Approach

Since the network is to be operated with a constant flow temperature, only a parallel configuration (compare figure 3) is specified. In order to ideally connect the existing heat sources and to avoid designing the respective heat exchangers for the maximal load, they can be connected in parallel or in series, depending on the temperature levels (table 2). The source and sink system of figure 4 is also capable to reject the waste heat of the CHP plant during single operation.

Table 2: Utilization of the different heat sources and sinks during various operating conditions

Operation mode	HP		CHP+HP/ HP+CHP	CHP	CHP+ORC	
Season	Winter	Summer	Winter	All seasons	Winter	Summer
Source/sink flow order	air → brine	brine → air	brine → waste heat CHP	CHP cooling → brine	brine → air / CHP cooling → brine	air → brine / CHP cooling → air

In order to adapt the cycle to these sliding temperature characteristics of the source-sink system and the heat network, the use of zeotropic working fluids is obvious. A simplified pre-design is performed using three operating points. Two of them represent the HP and ORC operation in the important seasonal transition period. For this purpose, a brine temperature of 10 °C is assumed. Based on the assumption of an isentropic efficiency of 0.7 and minimum temperature differences of 3 K in the heat exchangers and 5 K in the ORC evaporator for a propane butane mixture with equal proportions, the processes shown in Figure 5 are obtained (based on REFPROP 10: Lemmon et al., 2018). Both processes (Figure 5, right) can handle the temperature spread in the heating network and the maximum pressures remain below 25 bar.

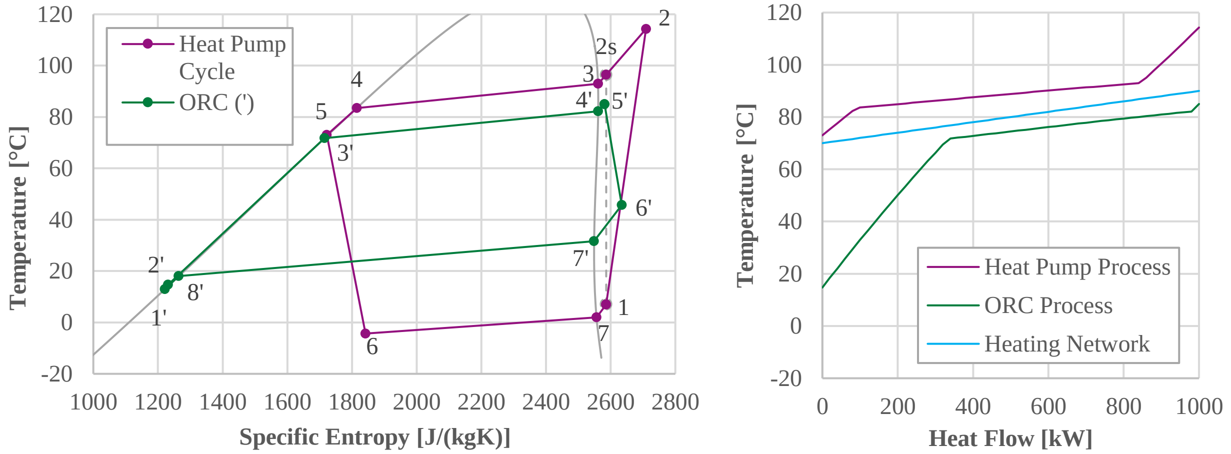

Figure 5: Heat pump and the ORC process with the working fluid mixture of 50 % propane and 50 % n-butane in a T,s diagram (left) and the temperature characteristic in the high temperature heat exchanger (right)

The third operating point is the CHP+HP mode where the brine can be heated to 45 °C by the waste heat. Following Dumont & Lemort (2019), the compatibility check between HP and ORC operation is performed via the Reynolds numbers at the individual state points. These should always be equal or smaller for the ORC process. In addition, the heat flow of 1,000 kW in the high-temperature heat exchanger should not be exceeded. A reversible screw machine is envisioned as the compressor-expander. It should be noted that the required volume ratios (V_i) and the volume flows of the low-pressure side ($\dot{V}_{screw,LP}$) in the screw machine differ greatly under the different operating conditions (Table 2). Thus, a wide capacity control via a frequency converter and a slide control is necessary. However, the machine can also be designed with two stages, using only the high-pressure stage for the "HP 45°C" and ORC operation mode (similar to Charalampidis et al., 2021). The low-temperature heat exchanger is the only component that must be explicitly designed for the larger capacity ($\dot{Q}_{HX,LT}$) of the ORC mode.

Table 2: Results of the pre-design of the reversible heat pump/ORC unit

	HP 10 °C	HP 45 °C	ORC 10 °C		HP 10 °C	HP 45 °C	ORC 10 °C
$\dot{Q}_{HX,LT}$	$567\ kW$	$748\ kW$	$925\ kW$	$V_{i,screw}$	10,1	3,7	3,9
COP or η_{th}	2,3	4,0	7,5 %	$\dot{V}_{screw,LP}$	$2363\ m^3/h$	$880\ m^3/h$	$777\ m^3/h$

4.3 Methodology

The study by Brandes et al. (2021) gives generation and load profiles in hourly resolution for the calendar weeks (CW) 15 and 42 of the year 2045 (transition period). On this basis, the prosumer operation can be calculated. First, a heat demand profile was created based on weather data from Dresden (DWD, 2021) for the reference years 2011 to 2015, on which the study is also based. This consists of a domestic hot water profile for residential buildings according to VDI 6002-1 (VDI, 2014) and on a linear heating profile between 15 °C and a nominal heating demand at -12 °C. In each case, the hourly values were normalized to a maximal load. Due to high assumed refurbishment conditions, the share of domestic hot water heating is set to 25% of the total thermal load. The operating states are selected based on the considerations from Table 1. The need for feed-in is assumed for all hours, in which gas turbine and combined cycle power plants are under operation according to Brandes et al.

4.4 Results

As shown in Figure 6, the temperature profiles for Dresden do not differ significantly in the calendar weeks investigated. Thus, the heat load profiles hardly differ and range between 15% and 45% of an expected maximum heat demand. The profile of CW 42 is on average slightly lower due to the higher temperatures at certain times and a marginally lower demand for domestic hot water in October, in general.

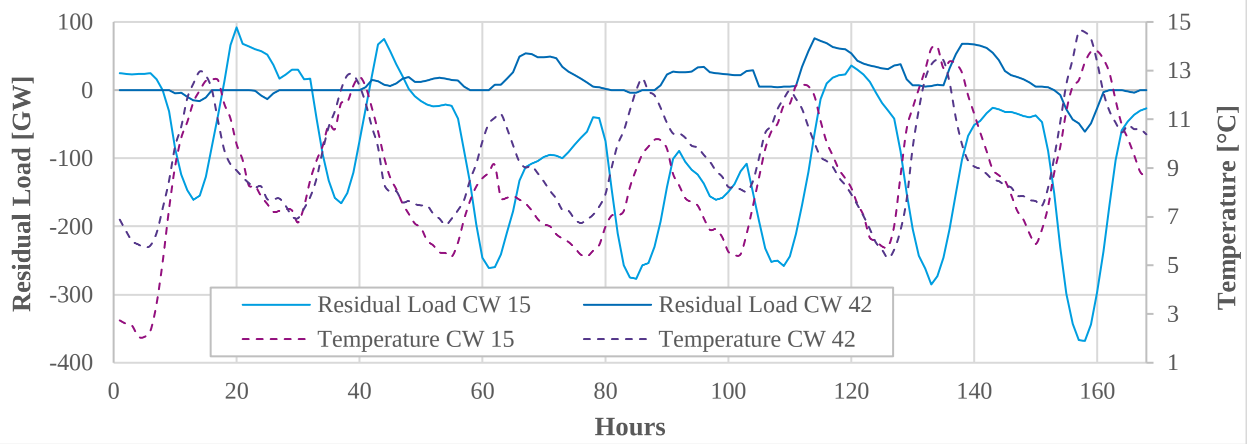

Figure 6: Data of the residual load in CW 15 and 42, 2045 according to Brandes el al. (2021) and the average temperature profile in Dresden of the years 2011 to 2015 in CW 15 and 42

The residual load, on the other hand, differs greatly in its profile and numbers. Due to a temporarily high feed-in from photovoltaics and wind in CW 15, the residual load fluctuates by 460 GW, but is negative on average. In CW 42, on the other hand, there is only a very low photovoltaics and wind feed-in on several consecutive days, requiring conventional generation. This has a decisive influence on the operating conditions of the considered prosumer. In Figure 7, its utilization is shown for the CW 42 normalized to the full load. It becomes obvious that there is a switch in the heat supply from the heat pump to the CHP plant in case of a positive residual load. In addition, conversion from waste heat to electricity using the ORC process is evident throughout much of the week due to the high electricity shortage.

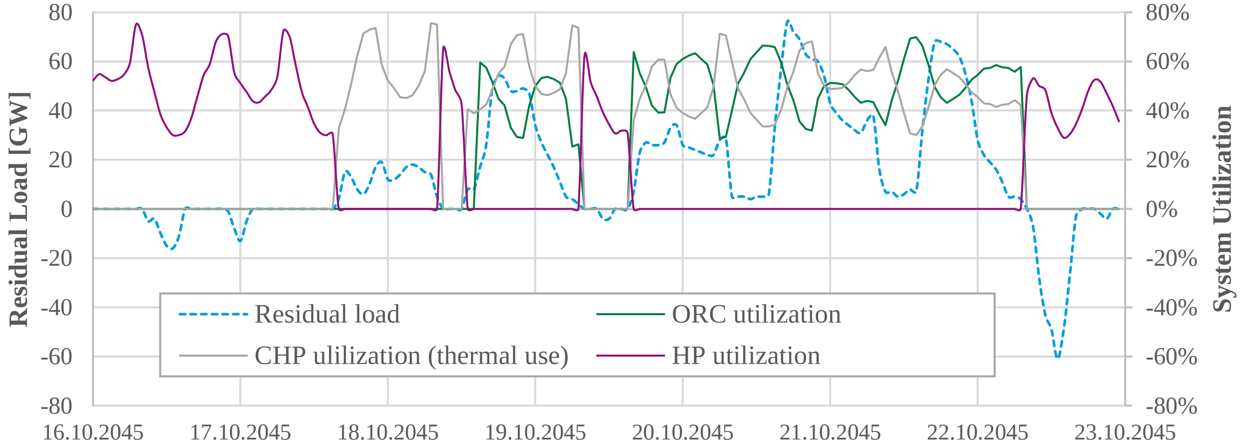

Figure 7: Residual load and resulting utilization of prosumer’s different operation modes in CW 42, 2045

In Figure 8, the calendar weeks are compared based on the operating frequency and the resulting full load hours in the different operating modes. In CW 15, heat pump operation dominates due to the availability of renewable energy. An ORC operation is only encountered in 18 hours and only briefly reaches a maximum utilization of 56% during this time. This is reflected in the low full load hours of 6.5. In CW 42, on the other hand, ORC operation represents the most frequent operating case of the reversible plant. A utilization of 100% is not achieved in these hours only because the CHP plant is thermally designed for only 50% of the maximum load. Only the difference between the maximum thermal output of the CHP plant and the current heating load can be converted into electricity. Thus, 40 full load hours are achieved. The operating modes of a combination of CHP plant with the heat pump, already identified as undesirable, do not occur for the assumption of average temperatures. With the variance of the temperature curve for CW 42, the basic design of a CHP plant and a heat pump of 50% of maximum load was verified further. For those minimal temperatures the CHP+HP mode occurs only in 5 hours, the HP+CHP mode only in one hour. In all of these hours the utilization of the second heat generator is negligible, which confirms the design according to current aspects.

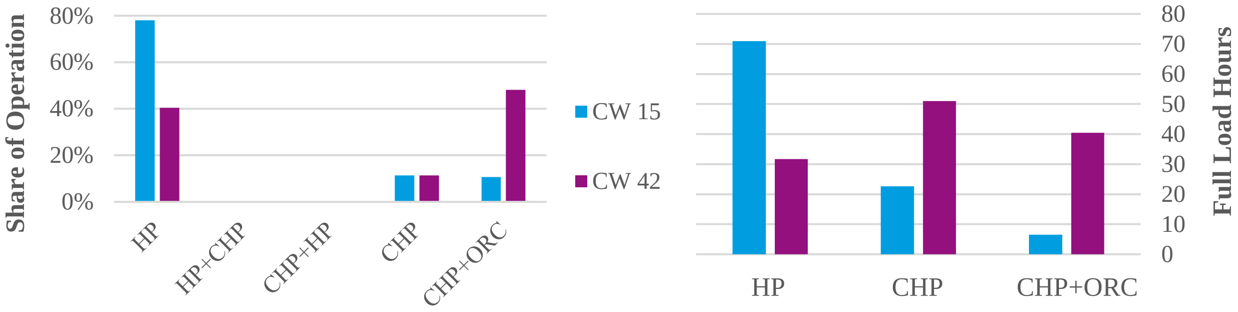

Figure 8: Comparison of the use of the different operation mode

Additional assumptions are made to determine hourly COPs and efficiencies. A brine temperature of 5 °C is taken for CW 15 and 15 °C for CW 42. The gradient from brine to ambient air is set to 3 K. Thus, the optimal primary heat source or sink can be determined in each case. As expected, the ORC and HP operations use air and ground inversely. Weighted by the hourly utilization, average COPs and efficiencies can be determined for CW 15 of 2.2 and of 8.3%, respectively, and for CW 42 of 2.5 and 7.2%, respectively. Thus, the best values of the respective process unfortunately occur inversely to the number of full load hours. For CW 42, it should nevertheless be emphasized that the ORC process can feed 23% of the electrical work required for the heat pump into the grid.

5. CONCLUSIONS

The findings developed on the use of CHP plants can be summarized as follows:

- As the availability of renewable electricity increases, the need to supplement CHP-fed grids with a heat pump becomes more important in order to avoid unnecessary CO_2 emissions from the combustion of fossil fuels.
- In the long-term, the full load hours of CHP units decrease, because they only take over the function of the heat producer in times of positive residual load. It should be noted, however, that periods of high residual load coincide with high heat demand.
- If high positive residual load requires operation of peak load power plants, the control strategy behind a CHP plant can be dictated by electricity demand (power-driven).
- Local CHP units only have a long-term perspective where they are supplied with renewable or synthetic fuel.

According to the state of knowledge and the current work, the following statements can be made about the use of a reversible HP-ORC unit in heating networks:

- In the three-digit kW and single-digit MW range, implementation of reversible HP-ORC units is possible with relatively little effort. Edge-controlled displacement machines are suitable as reversible compressor expanders. A pump must be added and the low-temperature heat exchanger must be able to transfer a larger heat flow. It is advantageous that the complex heat source system of the heat pump can be used as a sink.
- The rise in electrical efficiency of the CHP plant by up to 4 percentage points in the absence of a heat load is also possible with basic integration of a reversible unit in heating grids with a flow temperature of 90 °C.
- Significant operating and full load hours of ORC operation can be expected, especially during the transition period with moderate heating capacities and large fluctuations in the residual load.
- Currently, CHP plants are generally not designed for the maximum peak load. If these are complemented by a reversible plant, this does not yet directly lead to the possibility of reducing the addition of conventional generation peak load capacity. This is due to a simultaneous occurrence of positive residual load and heating load. However, a reduction would be possible if the waste heat from peak load power plants were fed into the heating networks. The upper limit would be that the total installed thermal waste heat capacity of the power plant fleet integrated in the heating network equals the maximum heat load plus the heat pump capacity. The reduction potential would then be equal to the capacity installed of reversible heat pumps in heat grids multiplied by the efficiency of the ORC plant.
- Reversible units in heating networks can be used in combination with a heat storage system as an integrated Carnot battery. The periods of use lie in summer, which would not reduce the conventional generation capacity addition, but the short-term storage capacity (battery storage) could be reduced by the same amount.

The analysis has shown that a Power and Heat Prosumer can be formed out of a CHP-fed heat network and a reversible HP-ORC unit. This has the long-term potential to reduce the addition of generation capacity required for a climate-neutral society with little technical effort. This opportunity should be considered in the current drive to integrate heat pumps into heat networks.

REFERENCES

Briem, S., Beckers, R., Bunkus, R., Fabris, Ch., Hoffmann, Herbstritt, C., Hofmeier, K., Krack, J., Nowack, A., Rother, St., Schuberth, J., Steinbrenner, J., Sternkopf, R., Unnerstall, H., Vollmer, C. (2020). Status quo der Kraft-Wärme-Kopplung in Deutschland. Umwelt Bundesamt, Dessau-Rosslau, Germany.

Braasch, Ch., Nieratschler, W., Doering, St., Muscheid, M. (2017). Integration von Hochtemperatur-Wärmepumpen in KWK-Anlagen. *BWK: das Energie-Fachmagazin*, July 2017.

Brandes, J., Haun, M., Wrede, D., Jürgens, P., Kost, Ch. & Henning, H.-M. (2021). Wege zu einem klimaneutralen Energiesystem: Die deutsche Energiewende im Kontext gesellschaftlicher Verhaltensweisen; Update November 2021: Klimaneutralität 2045. Fraunhofer-Institut für Solare Energiesysteme ISE, Freiburg, Deutschland. Available on https://www.energy-charts.info/index.html?l=en&c=DE.

Charalampidis, A., Braimakis, K. & Karellas, S. (2021). Design of a reversible Heat Pump/ORC Unit for a Renewables-based Trigeneration System. *Proceedings of 6th Int. Seminar on ORC Power Systems, Munich, Germany.*

Deutscher Wetterdienst (2021). Klimadaten Deutschland, Station Dresden-Klotzsche, historisch. 30.03.2021

Dumont, O., Quoilin, S. & Lemort, V. (2015). Experimental investigation of a reversible heat pump/organic Rankine cycle unit designed to be coupled with a passive house to get a Net Zero Energy Building. *Int. J. Refrig.*, *54*, 190-203.

Dumont, O. &, Lemort, V. (2019). Thermo-technical approach to characterize the performance of a reversible heat pump/organic Rankine cycle power system depending on its operational conditions. *Proceedings of the 32th Int. Conference of ECOS, Wroclaw, Poland*.

Dumont, O., Frate, G. F., Pillai, A., Lecompte, St., De Paepe, M. & Lemort, V. (2020). Carnot battery technology: A state-of-the-art review. *Journal of Energy Storage*, 32.

Dumont, O., Charalampidis A. & Lemort, V. (2021). Experimental Investigation of a Thermally Integrated Carnot Battery using a Reversible Heat Pump/ Organic Rankine Cycle. *Proceedings of 18th International Refrigeration and Air Conditioning Conference at Purdue, USA.*

European Parliament and Council, (2021). Regulation of establishing framework for achieving climate neutrality and amending Regulations (EC) No 401/2009 and (EU) 2018/1999 ('European Climate Law'), 30 June 2021.

International Energy Agency (2008). Combined Heat and Power: Evaluating the benefits of greater global investment. Paris, France: IEA Publications.

International Energy Agency (2021). Net Zeroby 2050: A Roadmap for the Global Energy Sector. Paris, France: IEA Publications.

Jennbacher (2022). Technical Details of Type 4 for H2. https://www.innio.com/en/jenbacher/solutions/power-generation/hydrogen-fired-power-generation/technical-details-of-type-4-for-h2 (visit on 2022, 24th March).

Larson, E., Greig, C., Jenkins, J., Mayfield, E., Pascale, A., Zhang, C., Drossman, J., Williams, R., Pacala, S., Socolow, R., Baik, EJ, Birdsey, R., Duke, R., Jones, R., Haley, B., Leslie, E., Paustian, K & Swan, A. (2020). Net-Zero America: Potential Pathways, Infrastructure, and Impacts. Interim report. Princeton: Princeton University.

Lemmon, E.W., Bell, I.H., Huber, M.L. & McLinden, M.O. (2018). NIST Standard Reference Database 23: Reference Fluid Thermodynamic and Transport Properties-REFPROP, Version 10.0, National Institute of Standards and Technology, Standard Reference Data Program, Gaithersburg.

Raza, A., Gholami, R., Rezaee, R., Rasouli, V. & Rabiei, M. (2019). Significant aspects of carbon capture and storage – A review. *Petroleum*, 5(4), 335-340.

Steger, D., Karl, J. & Schlücker, E. (2021). Launch and first experimental results of a reversible heat pump-ORC pilot plant as Carnot Battery. *Proceedings of 6th Int. Seminar on ORC Power Systems, Munich, Germany*.

Sterchele, Ph., Brandes, J., Heilig, J., Wrede, D., Kost, Ch., Schlegl, Th., Bett, A. & Henning, H.-M. (2020). Wege zu einem klimaneutralen Energiesystem: Die deutsche Energiewende im Kontext gesellschaftlicher Verhaltensweisen. Fraunhofer-Institut für Solare Energiesysteme ISE, Freiburg, Germany.

US Department of State & US Executive Office of the President (2021). The long-term Strategy of the United States: Pathways to Net-Zero Greenhouse Gas Emissions by 2050 Washington DC, USA.

Verein Deutscher Ingenieure (2014). VDI 6002-1: Solar heating for potable water Basic principles System technology and application in residential buildings, March 2014.