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Evaluation of a Local Heating Network Supplied by a Pyrolysis Plant

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Abstract. In order to mitigate climate change, a wide range of negative emission technologies, such as pyrolytic carbon capture and storage, must be used in the future. This study therefore examines a specific application example for the energy supply with a pyrolysis plant that is operated with locally available biomass in the smallest district of the city of Freiburg. It is shown that such a supply concept is feasible and that the economic efficiency of the supply concept depends on the system output as well as the amount of local biomass and the revenues from the sale of the biochar. Of the six pyrolysis plants examined, two proved to be a promising alternative to the current wood chip boiler. By switching to an energy supply with a pyrolysis plant, the district could save several hundred tons of CO_2 per year. The resulting total negative emissions would amount to almost 1200 tons of CO_2 per year.

Keywords: Negative Emissions, PyCCS, Biochar

1. Introduction

To achieve the goals of the Paris agreement, it is not enough to only cut CO_2 emissions to net-zero, but it is inevitable to use and expand negative emission technologies to capture CO_2 from the atmosphere [1, 2]. To reach the goal of limiting the temperature increase to 1.5 °C by the year 2100, more than 800 gigatons of CO_2 must be removed from the atmosphere [3].

Pyrogenic carbon capture and storage (PyCCS) is a negative emission technology that allows us to actively remove carbon from the atmosphere and store it for the long term by following a few process steps. In the first step, plants remove CO_2 from the atmosphere to build biomass. In the next step, the biomass is pyrolyzed and thus converted to biochar, bio-oil, and pyrogas (syngas), mainly consisting of CO, CO_2, H_2, and CH_4 [4]. In the last step, the biochar and bio-oil are processed in such a way that they cannot oxidize and release the containing carbon back into the atmosphere [4]. One possible application is the use of biochar for soil amendment. This way, the contained carbon remains there for several hundred years, depending on the chemical composition of the biochar, which in turn depends largely on the temperature during pyrolysis [4–6]. Moreover, the environmental conditions of the storage, like temperature and moisture, play an important role in the persistence of biochar in soil [5]. The carbon content of biochar typically has values between 75% and 85% [4]. One ton of biochar with a carbon content of 80% contains the carbon of more than 2.9 tons of CO_2.

By now, there are already market-available technologies for pyrolysis plants. These plants convert biomass and gain pyrogas, which is energetically used. Biochar is produced as a side product and can be sold. In addition to heat, some pyrolysis plants also generate electricity in the form of combined heat and power (CHP). Besides the differences in the technology the pyrolysis plants use to provide energy, other differences come from the type of biomass that the pyrolysis plants can convert and the ratios of biomass input to biochar output. Most pyrolysis plants operate with wood chips as feedstock. Some plants can also use a more versatile mix of different kinds of biomasses by additionally converting biomasses such as green waste and animal manure.

For this investigation, the option of replacing a wood chip boiler as the base-load heat supply for a small district heating network by a pyrolysis plant was analyzed under energetical, economic, and ecological aspects. One-year average climate data (test reference year for the city of Freiburg from the Deutscher Wetterdienst) with a heating period from October to April was used. In the studied district, there is an animal park that produces large amounts of organic matter from agriculture and animal husbandry. That biomass is currently not used and could potentially be used in a pyrolysis plant. Furthermore, another municipal enterprise, two greenhouses, a restaurant for park visitors, and five residential buildings belong to the district. The current energy supply of the district network consists of a wood chip boiler combined with a peak-load oil boiler for heat supply and electricity purchase from the electrical grid. The temperatures in the local heating network are 90 °C for the supply flow and 60 °C for the return flow. For efficiency reasons, the district network includes a heat storage with 100 m³ volume. This current energy supply serves as the reference system for the investigated scenarios.

An assessment tool developed in MS Excel calculates the energy supply of the district based on the heat and electricity demand for different pyrolysis plants as well as the reference system. The selection of the pyrolysis plants was based on the relevance of the manufacturers on the market and the availability of information. Furthermore, different technologies should be mapped to identify potential advantages and disadvantages.

2. Methodology

2.1. Energy demand of the district

The basis of the calculations are the heat and electricity load profiles of the district. As the heat demand of most buildings was not known, load profiles were generated with a building model according to DIN EN ISO 52016-1 [7]. For the electricity demand, load profiles from electric meter measurements were available from the local energy supplier for all commercial buildings. The demand profiles of the residential buildings were simulated with the open-access software SynPRO [8] from the Fraunhofer ISE. The resulting total heat demand is 1281 MWh during the heating period, and the total electricity demand is 501 MWh for the whole year.

2.2. Biomass for conversion

Only dried biomass can be used as input material for the pyrolysis plants. For this reason, the moist biomass is dried first. The amount of moist biomass was determined by interviewing the responsible persons at the respective enterprises and converted into the equivalent dry substance (DS). A rough distinction can be made between the categories wood (60 to/a at 80% DS), green waste (420 to/a at 80% DS), and animal manure (533 to/a at 90% DS).

2.3. Pyrolysis plants

Market-available pyrolysis plants were integrated into the assessment tool, as well as the current wood chip boiler and peak-load oil boiler. For comparison, all pyrolysis plants had to be described with the same parameters. Technical specifications or prices were either requested and taken from the data sheets or derived from other pyrolysis plants. The following parameters were selected to describe all pyrolysis plants and are included in the calculations of the assessment tool:

- Electrical power
- Thermal power
- Biomass input rate
- Biochar output rate

In this study, nine supply concepts with six different pyrolysis plants were tested and compared to the supply with the wood chip boiler. The specifications of the pyrolysis plants, as well as the wood chip boiler can be found in Table 1. The plants from the manufacturer PYREG were tested for the input biomass wood chips and the biomass mix, as they can utilize both. The CW700-200+ was still included in the calculations, but the system is no longer produced by the manufacturer.

***Table 1**. The specifications of the studied biomass plants; * pyrolysis plants.*

Studied biomass plants	Electrical power [kW]	Thermal power [kW]	Biomass input [kg/h]	Biochar output [kg/h]
Reference wood chip boiler	-	600	174	-
PYREG PX 1500*	-	600	323	97
PYREG PX 1500 + ORC*	90	510	323	97
PYREG PX 500*	-	200	108	32
SynCraft CW700-200+*	220	328	161	13
SynCraft CW1200-400*	400	572	286	23
Carbon Technik Schuster cts 20*	225	733	300	100

2.4. Calculation

In the calculation, the heat storage serves as the energy balance for all positive (input) and negative (output) energy flows. Those heat flows include the heat produced by the pyrolysis plant and the oil boiler, the heat demand of the district, and heat losses of the storage and district network. During the heating period, the pyrolysis plant operates constantly at nominal power. The peak-load oil boiler modulates its power and starts when the pyrolysis plant cannot keep the storage set temperature. The supply temperature is 90 °C. The surplus heat from the pyrolysis plant is dissipated to the environment. The heat losses of the district network are estimated to be 30% of the annual heat input. Energy required to dry the biomass and the plant's own electricity requirements are not included in the calculation. A schematic layout of the heat supply, as implemented in the calculations, can be seen in **Figure 1**.

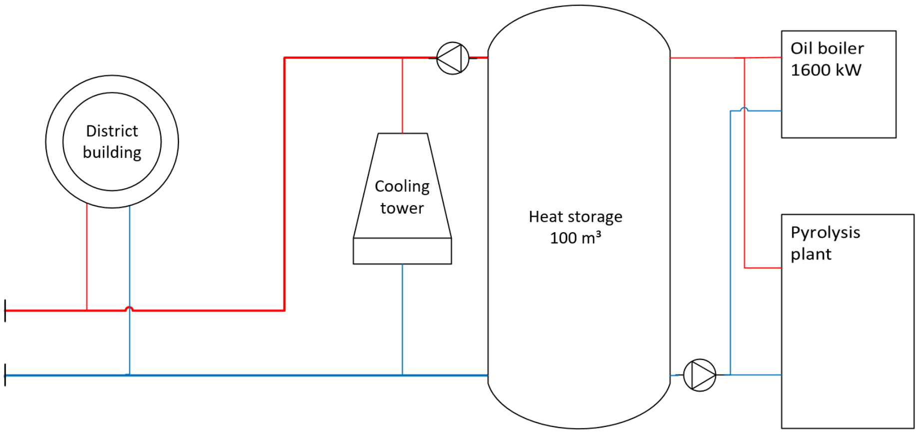

***Figure 1**. Schematic layout of the local heating network with heat storage (center), heat generators (right), consumers (left), and a cooling tower to dissipate the heat surplus.*

Costs and emissions are calculated from the calculation of the energy flows. The economic calculations are based on VDI 2067 [9], a guideline for calculating the economic efficiency of building installations. Like in the guideline, the economic efficiency is calculated as consistent costs over the review period by using the annuity method. For this investigation, the review period is 15 years, according to the depreciation period of a pyrolysis plant (assumed the same as for a wood chip boiler). The interest rate was set at 7%. Since the energy supply of the district consists of multiple heat generators and uses grid electricity, the annuity is calculated for the whole energy supply, including the pyrolysis plant, the peak-load oil boiler, and grid electricity for the whole year. The annuity of both heat generators is divided into the cost groups of capital-related costs, demand-related costs, and operation-related costs. The annuity of the pyrolysis plant is further expanded with revenues from payments of electricity from CHP plants and revenues from the sale of biochar. The operation-related costs of the pyrolysis plant are lowered by the amount of locally available biomass used for pyrolysis. Pyrolysis plants that can utilize a mixture of biomasses therefore achieve higher shares of autonomy than pyrolysis plants that can only utilize wood as feedstock, part of which needs to be purchased externally. The capital-related costs only include the investment costs of the heat generators. Further costs for the bagging plant, drying plant, or fuel tanks are not included. The revenues from the sale of biochar were determined by interviewing employees of the European Biochar Industry Consortium e.V. and estimated in the calculations at €250 per ton of biochar and a further €100 per C-sink certificate (1 certificate equals 1 ton of CO_2 removal). Deductions from the processing on the CO_2 removal potential are not considered. This results in revenues of €540 per ton of biochar with 2.9 tons of CO_2 equivalent. The expected prices of the pyrolysis plants range from €3,500/kW_{th} to €5,800/kW_{th}, depending on the manufacturer and the ratio of electrical output to thermal output of the plants. Pyrolysis plants with electricity generation are correspondingly higher within the range.

Just like the costs, the emissions were calculated annually for the whole energy supply concept, including the emissions of the pyrolysis plant, the emissions of the peak-load oil boiler, and the emissions from grid electricity consumption. Furthermore, the emissions of the pyrolysis plant are divided into negative emissions (NE) of the biochar (1 ton of biochar equals 2.9 to CO_2 NE) and emissions from the combustion of the syngas. Table 2 presents the CO_2 factors used for calculating the emissions caused by the different energy sources. These CO_2 factors are then multiplied by the energy content of all energy sources to calculate the respective emissions. In a further attempt to estimate the CO_2 emissions resulting from the combustion of the syngas, it is assumed that all carbon not contained in the biochar after pyrolysis is released into the atmosphere as CO_2. The CO_2 emitted during the processing steps up to the application of the biochar is not included in the calculations.

Table 2. *CO_2 factors for the different energy sources [10, 11]*

Energy source	**CO_2-factor [kg CO_2/kWh]**
Oil	0.266
Biomass wood	0.027
German electricity-mix 2020	0.432

3. Results and discussion

3.1. General findings from all investigated pyrolysis plants

The performance in energy utilization depends on the system output of the pyrolysis plants compared to the district's demand (see **Figure 2**). Therefore, systems with a high output of heat and electricity result in higher coverage regarding the energy demand, which in turn means less heat to be provided by the peak-load boiler or electricity purchased from the electrical grid. However, pyrolysis plants with a high thermal output also have a high heat surplus that gets dissipated, as they are operated continuously at nominal power during the heating period.

For the economic efficiency of the supply concepts with a pyrolysis plant, several parameters were found to have an influence on the total annuity. In particular, the total annuity depends on the amount of biomass produced by the animal park that can be used for pyrolysis. This reduces the amount of wood chips that must be purchased and lowers the demand-related costs. Especially plants that can use the full biomass mix of the animal park prove to be useful since the wood component is very low (≈ 6 wt.%) compared to the rest of the organic matter. In addition, it has been shown that biochar, which is a by-product during pyrolysis, generates important revenues. Therefore, a high biochar production is not only reasonable regarding emissions but also has a positive effect on the operation-related costs of a pyrolysis plant. Finally, a dependency on electrical output could be worked out for economic efficiency due to savings by self-produced electricity and additional revenues from electricity feed-in. Ideally, the electrical output of a pyrolysis plant covers just the base-load of the district, as plants that produce more electricity cause higher investment costs, which are not compensated by revenues from the feed-in of CHP electricity.

The total emissions of the supply concept are most importantly influenced by the biochar production rate of the pyrolysis plant, as these generate negative emissions. From the results of the emission calculation, the supply concepts with the highest biochar production have the lowest emissions. Moreover, the total emissions are influenced by the thermal and electrical output of the individual pyrolysis plant. Pyrolysis plants with a high coverage of the heat demand cause less emissions generated by the peak-load boiler. A high coverage of the electricity demand results in lower emissions due to the purchase of grid electricity. Supply concepts in which the pyrolysis plant has a high coverage of the heat and electricity demand and, at the same time, has a high biochar production are the most advantageous in terms of emissions. Nevertheless, all the investigated supply concepts with a pyrolysis plant result in far lower CO_2 emissions than the current supply with the wood chip boiler and the purchase of grid electricity.

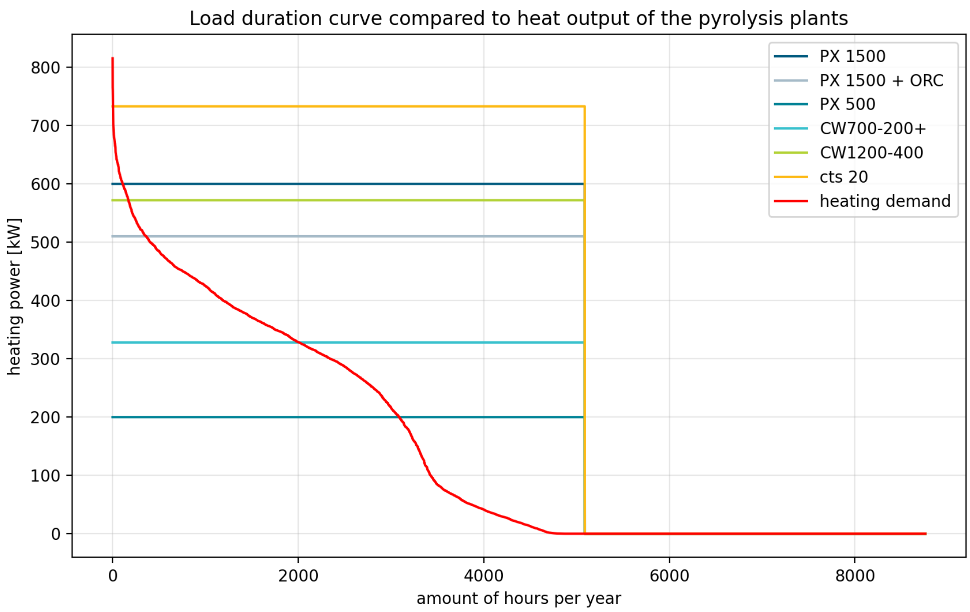

Figure 2. *Observation of the sorted load duration curve and the heat output of the different pyrolysis plants, both during the heating period.*

3.2. Evaluation for the district

The results of the calculations show that two supply systems with a pyrolysis plant generate lower costs than the reference system with the wood chip boiler (see Table 4). This applies to the supply concepts with the PX 1500 pyrolysis plant, both with and without add-on ORC module if they are operated with the entire biomass mix. In this case, around 61.7% of the biomass required for pyrolysis can be covered by own production. When operating only with the wood component, none of the supply systems examined could be operated economically compared to the reference system, as the wood chip boiler can already cover 11.2% of its fuel requirements by using the wood component alone. In addition, the PX 1500 plant has a high biochar production and thus generates high revenues from the sale of biochar, including C-sink certificates. This high biochar production by the plant also ensures high negative emissions.

The best results in terms of energy utilization, economic efficiency, and environmental impact are achieved by the supply system with the PX 1500 plant with the additional ORC module. The thermal output of 510 kW and the electrical output of 90 kW of the plant configuration are well suited for the district. This means that the system covers 98% of the heat demand and 97% of the electricity demand during the heating period and, at the same time, has a moderate heat and electricity surplus (see Table 3). Also, that supply system reaches the lowest annuity due to the well-dimensioned system output. Although the ORC module means additional investment costs, the annuity of the overall energy supply is ultimately more favorable than for the PX 1500 without the extension. Finally, the supply concept with the PX 1500 plant with the ORC module also has the lowest emissions of the two economical supply concepts. The example of the PX 1500 clearly shows that the addition of an ORC module slightly increases the emissions of the peak-load boiler due to the reduced thermal output, while the emissions from electricity consumption decrease due to the electrical output of the plant. As a result, the system configuration with ORC module has lower overall emissions (see Table 5), while forcing the same amount of negative emissions from similar biochar production. In one year, the supply system with the PX 1500 with ORC module can save more than 1400 tons of CO_2 compared to the wood chip boiler, at around €54.900 lower costs per year.

Table 3. *Results from the calculation of the energy utilization for the reference system and the pyrolysis plants.*

Base-load energy generator	**Heat coverage**	**Electricity coverage**	**Heat surplus**	**Electricity surplus**
Wood chip Boiler	99.8%	-	-	-
PX 1500	99.8%	-	39.7%	-
PX 1500 + ORC	98.0%	97.3%	30.4%	35.6%
PX 500	54.3%	-	1.7%	-
CW700-200+	80.2%	100%	11.5%	72.9%
CW1200-400	99.7%	100%	36.8%	85.1%
cts 20	99.9%	100%	50.6%	73.5%

Table 4. *Results from the calculations of the economic efficiency in relation to the biomass used for energy generation and the coverage of the fuel requirements for the reference system and the supply with the pyrolysis plants.*

Base-load energy generator	**Biomass feedstock**	**Local biomass coverage**	**Total annuity [€/a]**
Wood chip Boiler	Wood chips	11.2%	391,307
PX 1500	Biomass mix	61.7%	380,182
PX 1500 + ORC	Biomass mix	61.7%	336,456
PX 500	Biomass mix	100%	437,581
PX 1500	Wood chips	3.7%	534,991
PX 1500 + ORC	Wood chips	3.7%	491,264
PX 500	Wood chips	11.0%	516,839
CW700-200+	Wood chips	7.3%	556,098
CW1200-400	Wood chips	4.1%	805,261
cts 20	Wood chips	3.9%	638,664

Table 5. *Results from the emissions calculation broken down by the origin and in total for the reference system and the supply with the pyrolysis plants.*

Base-load energy generator	**Emissions pyrolysis plant [to CO_2/a]**	**Emissions peak-load boiler [to CO_2/a]**	**Emissions grid electricity [to CO_2/a]**	**Emissions total [to CO_2/a]**
Wood chip Boiler	58	1	217	276
PX 1500	-1270	1	217	-1053
PX 1500 + ORC	-1270	11	89	-1170
PX 500	-424	249	217	42
CW700-200+	-104	108	86	90
CW1200-400	-185	2	86	-97
cts 20	-1329	1	86	-1243

Based on the annually accumulated net present values, it can be seen from which year onwards one system outperforms another, and which system performs best in the end. The cumulative net present value of the PX 1500 with the add-on ORC module is higher than that of the wood chip boiler from the twelfth year onwards when using the biomass mix. The net present value of the PX 1500 without extension exceeds that of the reference system in the 15th year (see **Figure 3**).

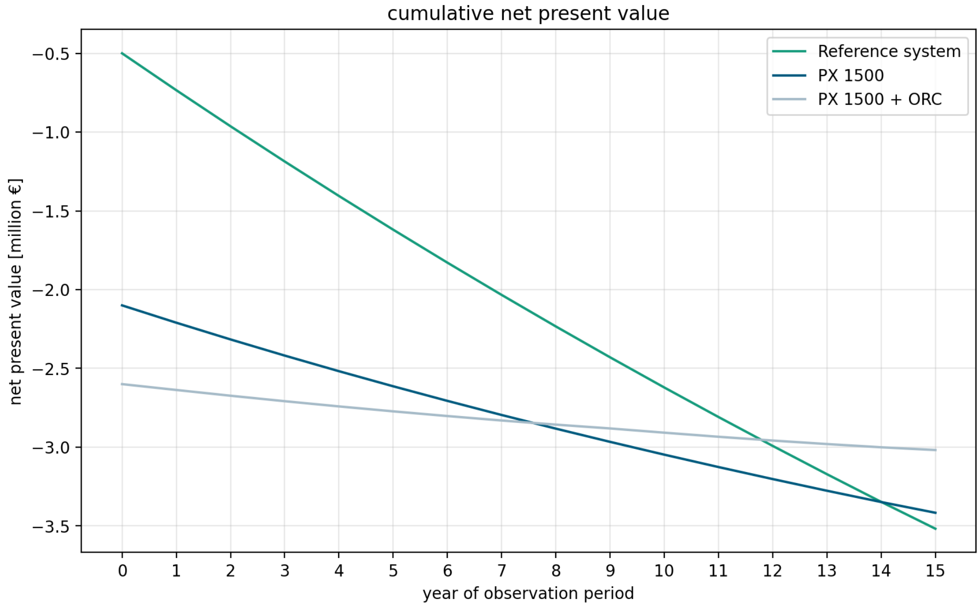

Figure 3. *Development of the net present values of the reference system with wood chip boiler and the supply concepts with the PYREG PX 1500 pyrolysis plant with and without additional ORC module operated with the biomass mix over the observation period of 15 years.*

3.3. The role of the respective prices

To gain a better understanding of how the profitability reacts to price changes, a sensitivity analysis was carried out for the supply concept with the PX 1500 pyrolysis plants (see **Figure 4**). For this purpose, the prices for grid electricity, wood chips, biochar, and C-sink certificates were varied by +/- 20%. The analysis for the PX 1500 plant yields the same observations as described above. The total annuity remains fairly stable with price changes for wood chips, as the PX 1500 is operated with approximately 62% locally available biomass due to its ability to utilize the entire biomass mix of the animal park. In contrast, the total annuity reacts very sensitively to changes in the price of biochar and C-sink certificates due to the plant's high biochar production. For the PX 1500 plant with the additional ORC module, the system is significantly less sensitive to price changes of grid electricity than the PX 1500 plant without the ORC module, as the electricity demand during the heating period is almost completely covered by the plant's own electricity generation.

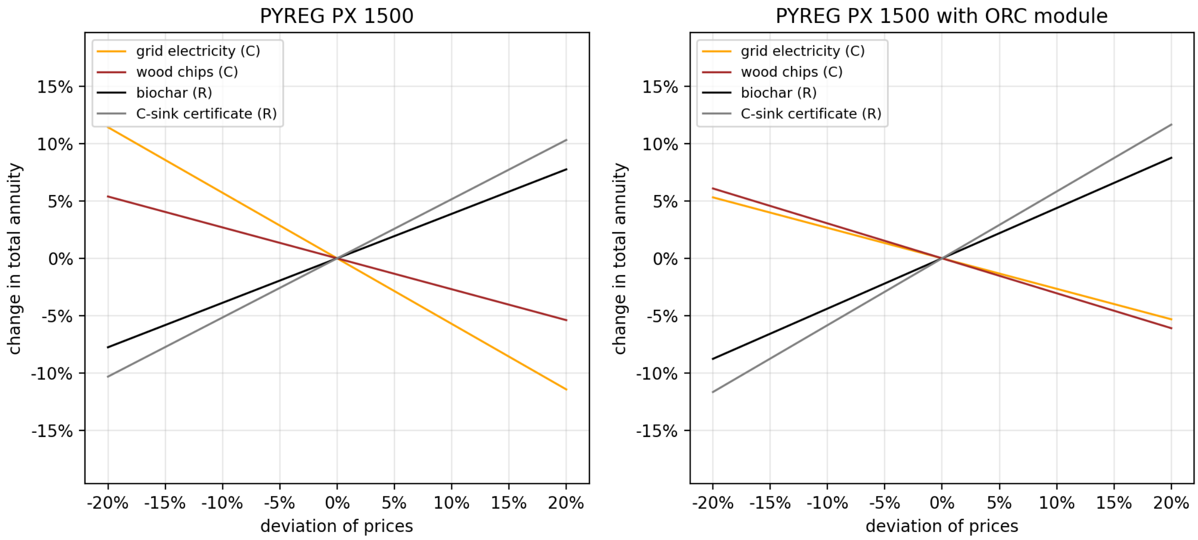

Figure 4. *Sensitivity analysis for price changes in costs (in legend marked with C) and revenues (in legend marked with R) for the parameters grid electricity, wood chips, biochar, and C-sink certificate for the PYREG PX 1500 pyrolysis plant with and without additional ORC module operated with the biomass mix.*

4. Conclusion

In this work, a holistic supply concept for the energy supply with pyrolysis plants was developed that reflects energy use, economic efficiency, and environmental impact. It should be noted that simplifications have been made, which may lead to deviations in reality. In summary, it can be said that energy supply with pyrolysis plants can be a sensible alternative to conventional concepts, although the profitability depends very much on the individual case. Especially the availability of organic substrate as feedstock must be highlighted as a decisive factor in that regard. A pyrolysis plant can be a suitable concept for large companies with high heat and electricity demands in particular, which will maximize the share of self-consumed energy. An application that does without the summer break could also deliver significantly better results.

For the district, the PX 1500 with the ORC module is a suitable system, as it can utilize the entire biomass.

Data availability statement

The underlying data can be accessed via the repository Fordatis.

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Author contributions

The authors have made the following contributions.

Michael Schölles:

- Data Curation,
- Formal analysis,
- Investigation,

- Methodology,
- Validation,
- Visualization,
- Writing – original draft

Harald Bier:

- Conceptualization,
- Funding acquisition

Björn Nienborg:

- Conceptualization,
- Methodology,
- Project administration,
- Supervision,
- Writing – review & editing

Competing interests

The authors declare that they have no competing interests.

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References

[1] J. Hilaire *et al.,* "Negative emissions and international climate goals—learning from and about mitigation scenarios," 2019, doi: 10.1007/s10584-019-02516-4.

[2] J. Rockström, O. Gaffney, J. Rogelj, M. Meinshausen, N. Nakicenovic, and H. J. Schellnhuber, "A roadmap for rapid decarbonization," *Science (New York, N.Y.)*, vol. 355, no. 6331, pp. 1269–1271, 2017, doi: 10.1126/science.aah3443.

[3] C. Werner, H.-P. Schmidt, D. Gerten, W. Lucht, and C. Kammann, "Biogeochemical potential of biomass pyrolysis systems for limiting global warming to 1.5 °C," *Environ. Res. Lett.*, vol. 13, no. 4, p. 44036, 2018, doi: 10.1088/1748-9326/aabb0e.

[4] H.-P. Schmidt *et al.,* "Pyrogenic carbon capture and storage," 2018, doi: 10.1111/gcbb.12553.

[5] J. Lehmann *et al.,* "Persistence of biochar in soil," 2015, doi: 10.4324/9780203762264.

[6] M. Camps-Arbestain, B. Singh, T. Wang, H.-P. Schmidt, and J. E. Amonette, "A biochar classification system and associated test methods," 2015, doi: 10.4324/9780203762264.

[7] *DIN EN ISO 52016-1:2018-04, Energy performance of buildings - Energy needs for heating and cooling, internal temperatures and sensible and latent heat loads - Part 1: Calculation procedures (ISO 52016-1:2017),* Deutsches Institut für Normung, Berlin.

[8] Fraunhofer ISE, *SynPRO Simulator.* [Online]. Available: https://synpro-lastprofile.de/simulator/ (accessed: Jul. 31 2023).

[9] Verein Deutscher Ingenieure, "VDI 2067 Blatt 1:2012-09, Economic efficiency of building installations - Fundamentals and economic calculation,"

[10] Bundesamt für Wirtschaft und Ausfuhrkontrolle, "Informationsblatt CO2-Faktoren," 2022.

[11] Umweltbundesamt, "Entwicklung der spezifischen Treibhausgas-Emissionen des deutschen Strommix in den Jahren 1990 - 2022," 2023.