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Sustainable Heat Supply for Greenhouses with Heatpumps

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Abstract. The heating of greenhouses in Germany is yearly responsible for the emission of about 3 million tCO_2eq. In the small horticultural city of Straelen in North-west Germany, the possibility to partially replace the heat supply of greenhouses with heat pumps instead of CO_2-intensive coal and oil boilers has been investigated. Different scenarios based on the power of the heat pump and the type of source (air or ground) have been simulated and compared economically and ecologically. Over the lifetime of the whole system, the levelized cost of heat for a combined heat pump & gas boiler heating system is lower than the reference case (coal & gas boilers). The installation of a heatpump covering at least 70% of the yearly heat demand would reduce the CO_2-emission from minimum 70%.

Keywords: Heat Pump, Greenhouse, Simulation

1. Introduction

In view of the advancing climate change, greenhouses in commercial horticulture offer plants protection against increasing weather extremes and severe weather events. Further ecological and economic advantages result from a higher yield per area, lower water consumption, a reduction in pesticides, and a high recycling potential of water and nutrients. The amount of land taken up for glass greenhouses in Germany increased by around 30% to 4,828 ha between 2010 and 2021 [1]. Globally, a similar trend can be observed. However, heating the greenhouses requires high amounts of energy, which has so far been heavily based on fossil fuels. In 2015, about 2.6 TWh of primary energy was used to heat greenhouses in Germany, of which 28% came from hard coal, 21% from natural gas, and 15% from fuel oil; renewable sources (wood, biogas and plant-based oils) account for about 20% [2]. Estimates put the annual emissions from the heat and electricity demand of commercial greenhouses in Germany at around 3 million tCO_2eq.

To date, more than 90% of costs for energy in greenhouses are used for heating systems and similar figures are reported for Netherlands [3]. In this context, fluctuating prices for fossil fuels represent an enormous challenge for greenhouse operators in Germany - especially against the backdrop of the recent energy crisis.

One third of all houseplants and flowers in Germany is produced in the small town of Straelen in North-Rhine-Westfalen. For this reason, the project focused on this area, and was conducted together with the local Chamber of Agriculture and their test center. In order to decarbonize the plant industry and reduce future energy costs, the option of replacing a coal or oil boiler as base load heat supply for large greenhouses with a heat pump was analyzed under energetical, economic and ecological aspects.

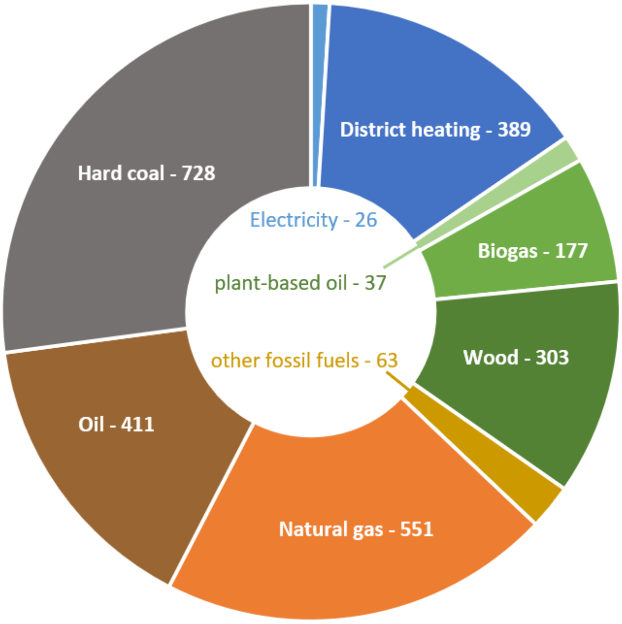

***Figure 1**: Energy sources used to heat greenhouses in 2015 (in GWh). Source: [2]*

2. Current technological state

As described previously, greenhouses are considerable heat consumers. Multiple glazing, which is commonly used in buildings to reduce heat loss, reduces the solar radiation that can be used for plant growth and is therefore not a practical solution. For this reason, movable energy screens and shading systems are primarily used to reduce heat loss to the surroundings at night or when there is very little radiation. They are controlled via fully automatic climate computers.

Greenhouses are usually heated via water-bearing pipes without active air circulation (cf. Figure 2) [4]. The water is usually heated using fossil-fired boilers. Occasionally, however, CHP or biomass combustion are also used. The specific heating capacity is up to 2 MW/ha, depending on the temperature requirements and the technical status of the envelope. The required flow temperatures are around 60°C. It is possible to reduce the flow temperature by using lamellar pipes, but this has rarely been cost effective in the past. Many heating systems are equipped with large buffer capacities (>100m³) for redundancy reasons and to cover maintenance periods.

***Figure 2:** Common heating systems – rail heating (left) and pipe wall heating (right)*

To reduce energy consumption, greenhouses nowadays have one or two energy screens. These prevent warm air from being trapped under the roof. In the cooler but bright months, transparent screens are used. In summer, on hot, very bright days, darker screens are used to reduce the greenhouse effect.

Dehumidification contributes significantly to heating energy consumption: Since many plants do not tolerate high humidity (risk of fungus), the ventilation flaps are opened and some of the air is exchanged for drier - but cold - ambient air. According to estimates, dehumidification is responsible for 20-30% of total heat consumption [5].

3. Methodology

To investigate the potential of a heat pump-based system, several scenarios have been simulated using Polysun, a software from Vela Solaris for holistic energy simulations of building or districts.

3.1 Heatprofiles

The load profile considered for the simulation is derived from the horticultural company Aflora, which operates 25,000m² of glasshouses. They mainly grow indoor plants and flowers, some of which require high heating temperatures up to 20°C. This company was visited as part of this project and was able to provide a lot of different data, including heating temperatures, heat demand profiles and purchase prices of energy sources.

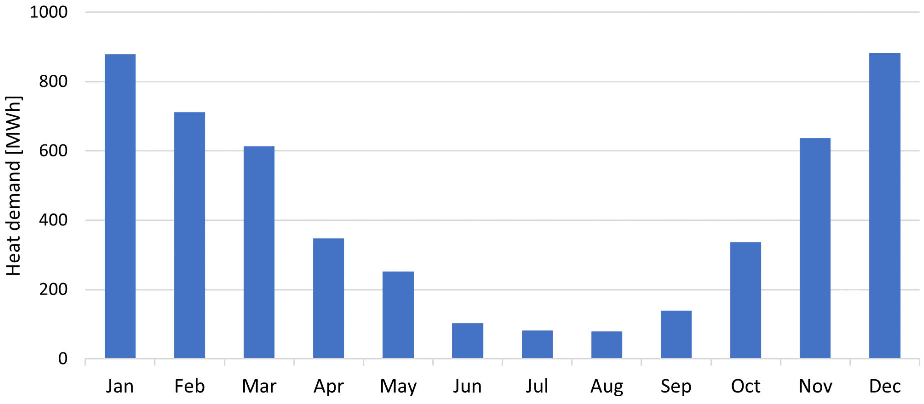

Figure 3: *Heating profiles and set temperatures of the horticultural business.*

The heat profile was calculated using the Software Hortex. The total annual demand is 5000 MWh, which matches the actual measurements of the company in the past 3 years with only 5% margin. The heat load is 4.5MW (1.8 MW/ha).

Two heating curves (correlation of ambient temperature and flow temperature) were developed based on the real settings and measurement from the company and are shown in Figure 4.

- The high temperature curve corresponds to the state of the art with the current operating settings: 75°C/55°C input/return temperature at -15°C outside temperature, and 40°C at 20°C outside temperature, in which case heating is no longer provided.
- The mean temperature curve corresponds to 55°C/40°C inlet/return temperature at -15°C outside temperature; these temperatures could be achieved with an adapted heat transfer system (e.g. finned pipes, active air circulation); the lower temperatures are clearly advantageous for heat pump operation, but they are associated with higher investments and possibly increased space requirements

3.2 Weather data

For the outdoor temperature, humidity and air pressure, the data from the DWD's test reference year (TRY) 2011 [6] has been used.

As can be seen on Figure 5 the city Straelen has a relatively mild climate: negative temperatures only occur 7% of the year.

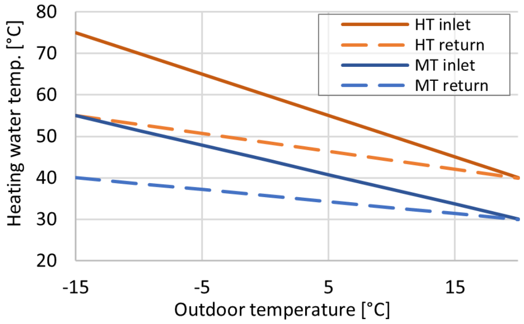

Figure 4: *Heating curves for high and medium temperature heating*

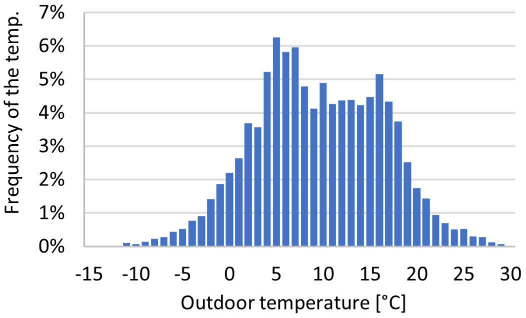

Figure 5: *Repartition of outdoor temperature over a whole year*

3.3 Simulated Scenarios

According to the local Chamber of Agriculture, horticultural growers in the Straelen region usually use a mixture of 2 or 3 energy sources to heat their greenhouses. There is always a gas boiler, at least for the peak load. Coal or heating oil is mainly used to cover the base load, also with the support of gas, depending on the respective energy prices. Many companies also have gas-powered CHP units for their own electricity production.

For these reasons, the heating system in the reference case consists of a coal and a gas boiler. The "wood chips & gas" scenario was examined, as wood chips are also a climate-friendly energy source, although the long-term and large-scale availability is uncertain. All heat pump systems have a gas peak load boiler and were each simulated with high heating temperatures (HT) and medium heating temperatures (MT) in order to evaluate the influence of this parameter.

Onsite visit has shown that air and geothermal probes are the only two sources that can be exploited with reasonable effort, and thus are considered in the simulation. The air source heat pump variants were also considered with two different nominal outputs: 1 MW and 1.5 MW. Throughout this report, the abbreviation "AW-HP" is used for "air-to-water heat pump" and "BW-HP" for "brine-to-water heat pump". An overview of the simulated scenarios can be found in Table 1.

Table 1: *all simulated scenarios*

Scenario	**Boiler**	**Heat pump**	**Heating temperatures**
Reference	1MW hard coal + 3.5 MW gas,	-	High (75/55)
Wood chips & gas	1MW wood chips + 3.5 MW gas	-	High (75/55)
1 MW AW-HP & gas, HT	3.5 MW gas	1 MW, source: air	High (75/55)

1.5MW AW-HP & gas, HT	3 MW gas	1.5 MW Source: air	High (75/55)
1 MW AW-HP & gas, MT	3.5 MW gas	1 MW Source: air	Medium (55/40)
1.5MW AW-HP & gas, MT	3 MW gas	1.5 MW Source: air	Medium (55/40)
1 MW BW-HP & gas, HT	3.5 MW gas	1 MW, source: ground	High (75/55)
1 MW BW-HP & gas, MT	3.5 MW gas	1 MW, source: ground	Medium (55/40)

3.4 Components

Figure 6 shows the system “1 MW AW-HP & gas, HT” in a simplified form. All variants with a heat pump are similar to this one. For the brine-to-water heat pump, the source is not air but geothermal probes.

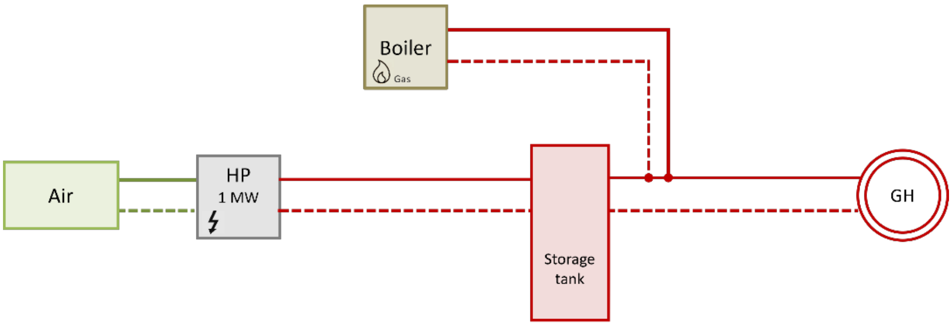

Figure 6: *Heating system with a 1 MW air-to-water heat pump and a gas boiler*

A storage tank of 100m³ is used in all scenarios, which corresponds to a volume of 4 l/m² of cultivated area. On-site data collection has shown that heat storage tanks of this size are common.

The heat pumps were configurated with generic performance data. The air-water heat pump has a COP of 2.8 at A7/W55, 2.24 at A-7/W55, and 4.08 at A2/W35.

4. Results

4.1 Energetical results

Figure 7 shows the amount of heat produced per energy generator as a relative proportion of the total annual heat demand, as well as the seasonal coefficient of performance (SCOP) of the heat pump. For an air-to-water heat pump and high temperature heating this number is 2.9 i.e. for 1 kWh of electricity consumption, the heat pump generates 2.9 kWh of heat. The brine-to-water heat pump has a better seasonal performance factor of 3.2 and can rise to 4.4 if the heating temperature is reduced.

The 1MW heat pump covers 68% of the total heat demand and up to 90% in the case of a brine-to-water heat pump and medium heating temperatures. A 1.5MW heat pump increases this proportion only slightly: only +4% in the case of an air-to-water heat pump with high heating temperatures or +8% for medium heating temperatures.

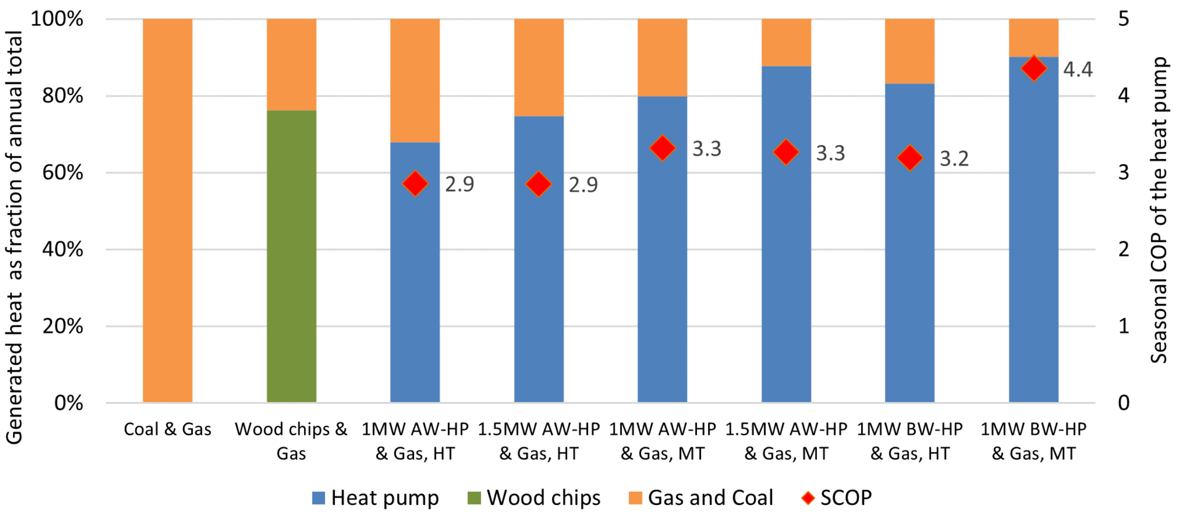

Figure 7: *Amount of heat generated per year and seasonal performance factor of the heat pump.*

4.2 Economical results

4.2.1. Cost assumptions

First, the total annual costs, consisting of energy and operating costs as well as annuities, were compared based on the annual amount of energy. Table 2 and 3 show the energy prices and investment costs used for the profitability calculation. The electricity prices were derived from [7], [8]. Although it is likely that a government subsidy will be available for the installation of a heat pump, it has not been considered here since the current transition to a new federal funding program creates some ambiguity.

Table 2: *Energy costs used for the economic analysis for the year 2024.*

Energy source	**Price (cts/kWh)**
Electricity	22.76
Gas	7
Coal	7.6
Wood chips	5

Table 3: *Investment costs for the economic analysis based on [7,8]*

Equipment	**Investment costs**
Air-to-water heat pump	900 €/kWth
Brine-to-water heat pump	580 €/kWth
Drilling & geothermal probes	33 €/m
Gas boiler	98 €/kWth
Coal boiler	137 €/kWth
Wood chip boiler	650 €/kWth
Storage tank	700 €/m³

The maintenance costs were simplified and estimated at 1.50% of the total investment per year for all systems. For the sake of simplification, the service life of the entire system was set at a flat rate of 20 years.

4.2.2 Assessment for the cost year 2024

The heat generation costs, defined as the annual costs divided by the annual amount of energy, are compared below. In addition to energy and maintenance costs, the costs also include the annualized investment over the service life. The various scenarios are each compared with the reference case "Coal & Gas".

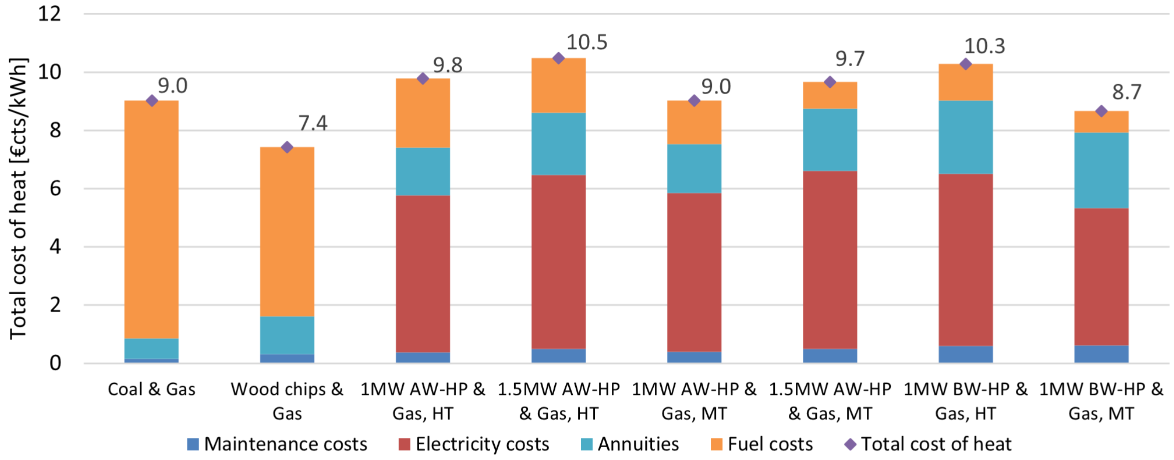

Figure 8: *Comparison of energy costs for all studied scenarios – year 2024*

Figure 8 shows that a heating system with hard coal and gas as energy sources is currently still cheaper than most scenarios with a heat pump. The 1.5 MW heat pump is not advantageous compared to the 1 MW variant: the share of heat demand covered by the heat pump only increases from 68% to 75%, while the investment increases by 31%. The brine-to-water heat pump, which requires high investment costs, is only of economic interest if it is combined with a reduction of heating temperatures (however, the costs for this are not included in the costs).

Wood chips are the cheapest energy source. However, biomass is only available in limited quantities and will probably be used for other applications in the future, and the price trend for this is particularly difficult to estimate.

The reduction in the heating temperature indicates potential for increasing economic efficiency, as it would, for example, reduce the heat generation costs with an air heat pump by around 10% from 9.8 cts/kWh to 9 cts/kWh. Over the entire service life of the systems (20 years), the savings add up to approx. 800T€, for a ground source heat pump even 1,600T€.

4.2.3 Sensitivity analysis

In the following, a sensitivity analysis is carried out for the scenario "1MW AW-HP, gas boiler, HT", in which various parameters are changed and thus their influence on the heat generation costs is determined.

Figure 9 shows among other things, that:

- an increase of 50% in the price of coal brings a clear advantage for the heat pump solution, as this becomes approx. 1.5 cts/kWh cheaper than the fossil fuel reference
- The price of gas has less influence, as a gas boiler is also used in the heat pump system for peaks.
- an increase of €60/t of the CO_2 price is enough to make a heat pump system cheaper than a 100% fossil-based system. According to a current forecast, this is very likely to be the case by 2030 [9], [10]

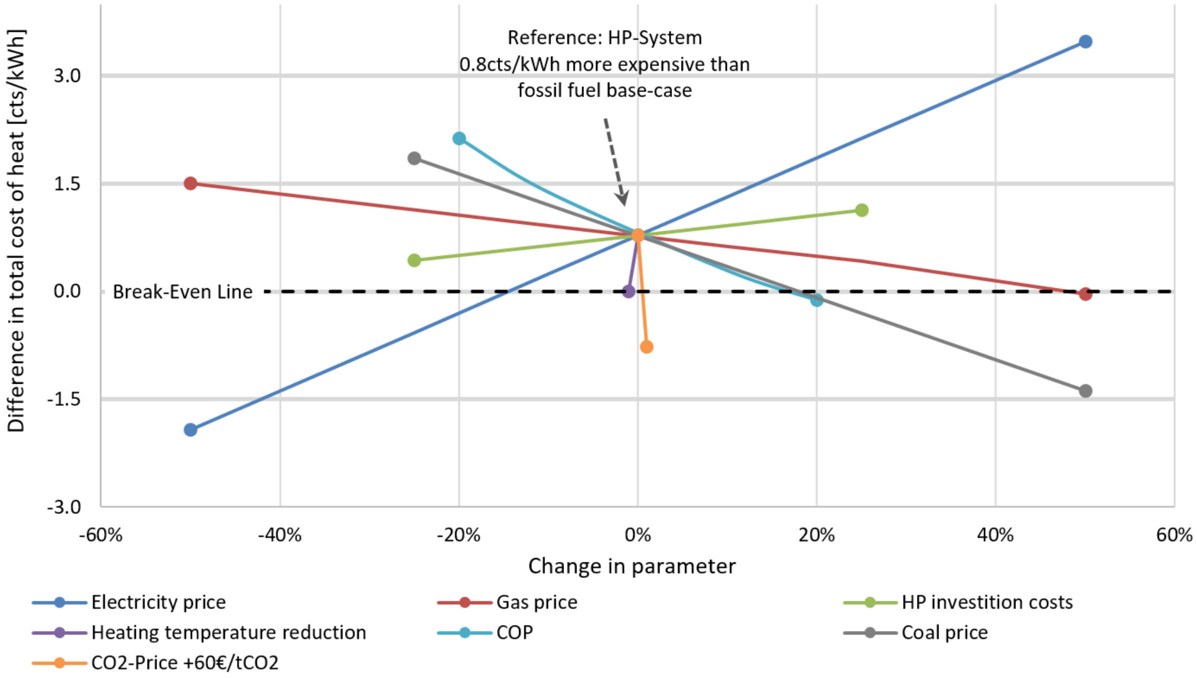

Figure 9: *Sensitivity analysis - comparison between fossil fuel reference case and 1MW AW-HP & gas*

4.2.4 Long-term assessment

As the decision on an alternative heating technology is a long-term investment, an analysis of the heat generation costs over the service life of 20 years was carried out. Three main scenarios were compared:

- Maintain the fossil-fuel reference system - no new investment required.
- Investment in a new 1MW air-to-water heat pump to cover the base load (scenario 1MW AW-HP & gas, HT)
- Investment in a new 1MW brine-to-water heat pump to cover the base load (scenario 1MW BW-HP & gas, HT)

It was assumed that the heat pump will be installed in 2024. The investment costs are divided over the entire service life of the heat pump in the form of annuities.

Table 4 shows the assumed CO_2, electricity, gas and coal prices between 2024 and 2045, based on [7], [11]. Prices are linearly interpolated between those years.

Table 4*: Assumed prices for the long-term analysis. Energy prices already include the CO2-tax.*

Year	**CO2 (€/tCO2eq)**	**Electricity price (€cts/kWh)**	**Gas price (€cts/kWh)**	**Coal price (€cts/kWh)**
2024	45	22,76	7,00	7,60
2025	47	19,05	8,39	7,65
2030	88	14,38	8,89	9,21
2035	139	14,07	9,72	11,12
2040	189	15,55	11,83	13,01
2045	172	13,91	11,09	12,38

The comparison in Figure 10 and 11 show that the total heat generation costs from 2026 onwards are already lower for an AW-HP than for the fossil-fuel reference system. The installation of a 1 MW air-to-water heat pump would therefore have a return on investment in 2028.

The resulting Levelized Cost of Heat for these three scenarios over the entire service life are:

- Reference (100% fossil): 11.47 cts/kWh
- 1MW AW-HP & gas: 9.06 cts/kWh
- 1MW BW-HP & gas: 8.78 cts/kWh

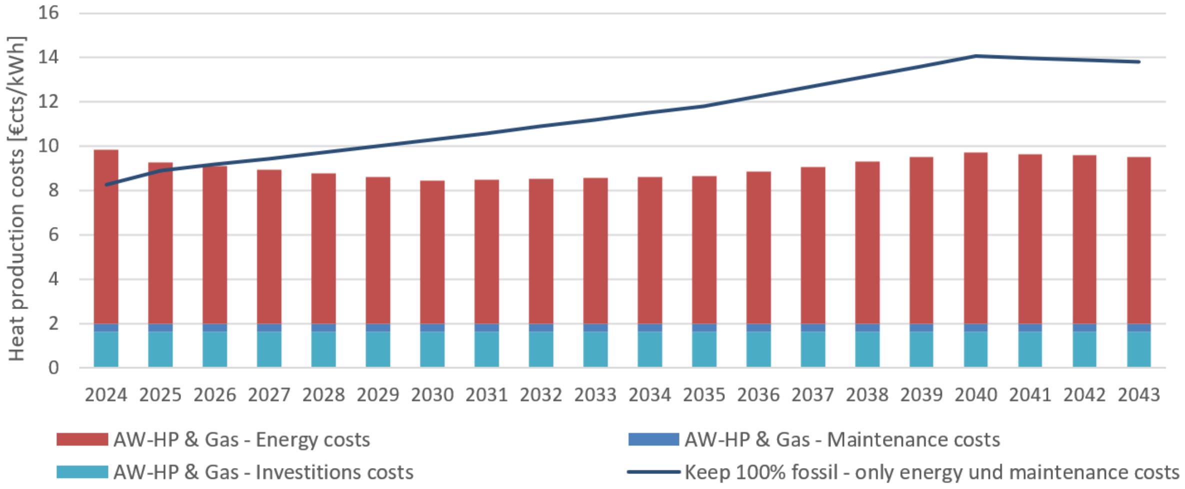

Figure 10: *Total costs of heating systems – comparison of the reference case against the air-to-water heat pump and gas system.*

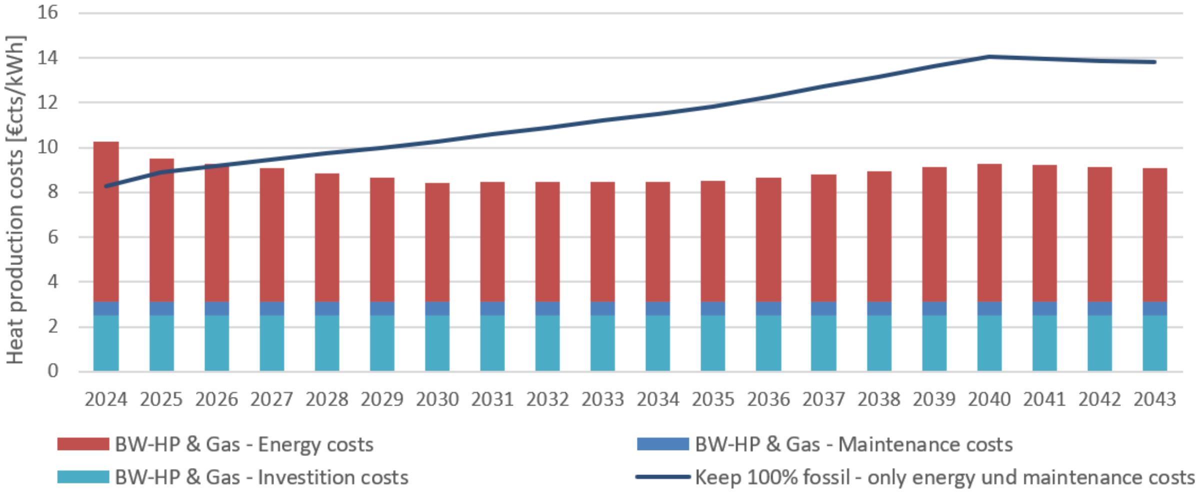

Figure 11: *Total costs of heating systems – comparison of the reference case against the brine-to-water heat pump and gas system.*

4.3 Ecological Assessment

For the environmental assessment, the annual greenhouse gas emissions in tCO_2eq of different scenarios were compared. *Table 5* shows the assumed emission factors for the various energy sources used. These were averaged over the entire service life of the plant. Figure 12 shows the results of this analysis: the installation of a 1MW air source heat pump would provide a 70% reduction in emissions. A larger 1.5MW heat pump increases this value to 75% but is uneconomical due to the higher investment costs (see previous chapter). In the best case of a ground source heat pump with a reduction in heating temperatures, the avoidance of CO_2 emissions would even amount to 87%.

***Table 5**. Average emission factors of various energy sources over the service life, based on [10]*

Energy Source	**Emission factors incl. upstream chain (gCO_2 /kWh)**
Electricity	120
Gas	240
Coal	433
Wood chips	24

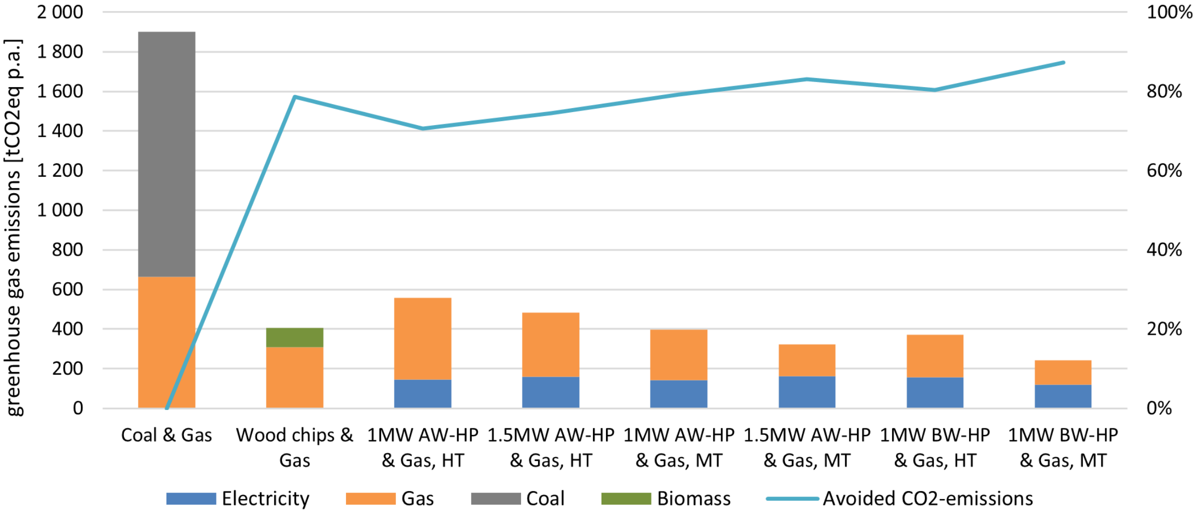

***Figure 12:** Comparison of yearly greenhouse gas emissions in tCO_2eq for all studied scenarios*

5. Conclusion

The results of the study conducted can be summarized as follows:

- Considering current forecasts for the price development of CO_2 and energy, heating systems for greenhouses that include heat pumps will already be cheaper than purely fossil-based producers in a near future.
- The CO_2 and electricity price have a major influence on economic efficiency. The influence of the gas price is less significant since a gas-powered boiler is also required for the peak load.
- The investment costs of the heat pump have a comparatively low influence on the heating total costs due to the high-capacity utilization.
- In the scenarios considered, the use of a heat pump reduces CO_2 emissions by 70% to 87% compared to the purely fossil reference system. However, a fossil-fuel peak load boiler will still be required for peak loads.

5.1 Possible further developments

The above results clearly show the economic and ecological potential of heat pumps for heating greenhouses. In view of the short-term economic break-even, now would be an ideal time to provide practical proof of technical feasibility and lay the foundations for broad acceptance of heat pumps in greenhouse applications with a demonstration project. In this context, further questions could be addressed, such as:

- Can the heat pump also be used for dehumidifying and/or cooling greenhouses in addition to heating?

- Is there potential to economically integrate PV in greenhouses in order to reduce the heat pump's grid power consumption?
- Which measures that increase the efficiency of the heat pump (e.g. reduction of the heating circuit temperature by increasing the surface area, reduction of heat losses, ventilation system with heat recovery for humidity control, ...) are cost effective?

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.

Matthieu Chaigneau:

- Data curation,
- Formal analysis,
- Investigation,
- Methodology,
- Validation,
- Visualization,
- Writing – original draft

Björn Nienborg:

- Funding acquisition
- Conceptualization,
- Methodology,
- Supervision,
- Writing – review & editing

Competing interests

The authors declare that they have no competing interests.

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