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Design and Comparative Analysis of a Renewable Energy Based Rural District Heating System

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Abstract. This research focuses on adapting renewable energy sources for high-temperature rural district heating systems. By utilising Polysun® software [1], simulations explore combinations of wood chips (biomass), air-water heat pumps, geothermal heat pumps and solar thermal. Emphasising carbon neutrality, the study considers the demand for space heating and domestic hot water. Data acquisition in Middle Franconia involved collecting relevant data from Hotmaps [2], considering the number of houses, construction year, and heated gross floor area. The study wraps up by presenting optimised models, empowering communities to make emission-effective decisions for sustainable heating solutions. This research contributes significantly to rural heating advancements, promoting energy efficiency and environmental sustainability. In our paper, we suggest solutions for rural energy communities with different technologies to reduce carbon emissions.

Keywords: Renewable Energy, District Heating, Wood Chips (Biomass), Air-Water Heat Pumps, Geothermal Heat Pumps, Solar Thermal, Hotmaps, Sustainable Heating

1. Introduction

Rural district heating is highly adaptable, offering flexibility in utilizing diverse energy sources and transitioning between them. Unlike the complex process of replacing numerous small boilers in individual buildings, modifications or exchanges can be efficiently done in one central unit [3]; this enables swift changes in the rural heating sector when favorable economic and political conditions align. Another reason is that rural district heating is very comfortable for the customer and needs only minimal maintenance and involvement from the user side. Rural district heating can also quickly heat many buildings in a CO_2 neutral way.

This research addresses the complex challenges rural heating communities face, including carbon dioxide reduction goals, an ageing population, volatile fuel prices (oil and gas), government restrictions, affordability concerns, self-sufficiency, and the need for energy independence. Rural district heating systems rely on technologies such as biomass-fired systems, combined heat and power (CHP), and decentralized approaches involving oil and gas.

2. Methodology

Motivated by achieving carbon neutrality by 2045, reducing dependency on fluctuating markets during pandemics and wars, increasing the utilization of renewable resources, and providing affordable heating solutions, this project employs a comprehensive methodology for different rural district heating systems. The first simulation (base scenario) shows the current heat supply using natural gas and oil. In the next step, the wood chips boiler is simulated. Biomass is in abundance in rural communities, nevertheless, the market can have an influence on the price. Subsequent simulations explore advanced and sustainable technologies, including combinations of wood chips boiler, air water heat pumps, geothermal heat pumps and solar thermal. Through these simulations, the research aims to identify approaches with the least carbon dioxide emissions, ultimately providing optimized options. This specifically focuses on space heating and domestic hot water demand, allowing communities to select heating solutions aligned with their carbon emission targets.

Data acquisition for a selected area, specifically the Middle Franconia region- Prühl (Oberscheinfeld), is done using Hotmaps [2]. This process can also be replicated for other regions. Factors considered include the number of houses, year of construction, heated gross floor area, and the exclusion of new renovation, focusing on existing building conditions. District heating is the efficient way to supply existing and historical buildings with large fractions of renewable heating (renovation to zero-energy houses is not possible here) [3]. The research involves designing the approach, conducting hydraulic simulations, and determining the dimensioning of heat generation devices and CO_2 emissions.

2.1 Polysun® Methodology

Polysun® software is a simulation tool for researchers and engineers to design and optimise renewable energy systems with precision [1]. The Polysun® [1] methodology includes key metrics to evaluate the performance and efficiency of simulated systems:

- **Etot (Total Energy Consumed):** This represents the total energy consumed, covering fuel and electrical power consumption needed to operate heat generators, electrical components, pumps, and associated infrastructure in the simulation system. This metric offers a straightforward measure of the energy requirements for sustained functionality.
- **Qaux (Supplied Heat Energy):** Quantity of heat energy supplied from electrical and fuel-operated heat generators, including electrical heating devices, to the fluid within the system. This metric comprehensively captures the amount of energy the specified heat sources contributed, serving as a vital indicator of the system's thermal dynamics and overall energy input.
- **Qdef (Heat Deficit):** Heat deficit represents the difference between the heat demand (Qdem) and the actual heat supplied (Qsup), reflecting the utilised energy within the system. This metric is crucial to assessing the shortfall, providing insights into the system's capacity to meet its energy needs.
- **Qdem (Total Heat Demand):** The total heat demand of the District/Buildings to be heated.
- **Qsup (Actual Heat Supplied):** The actual heat supplied to the District/Buildings.
- **η:** Represents thermal efficiency of the heat generator.
- **COP**: Coefficient of performance of the heat pump.

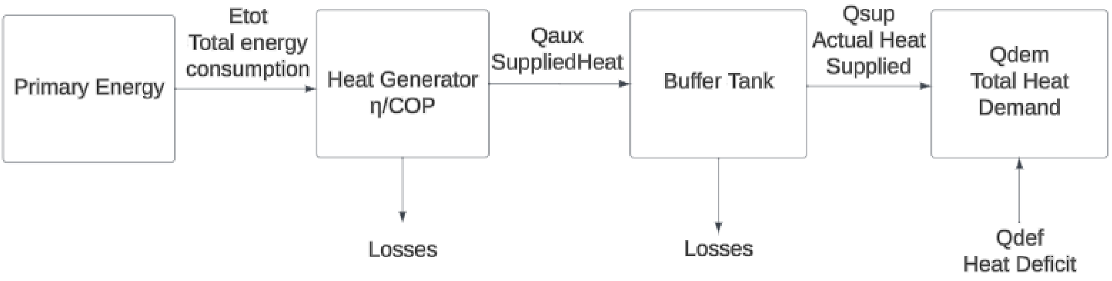

Figure 1. *Schematic block diagram representing Polysun® methodology.*

3. Results and Discussion

The Simulations in Polysun® software [1] represent an in-depth analysis of rural district heating systems integrating various technologies. The total heat demand (Qdem) of the rural village Prühl is 1161 MWh/a for a total gross floor area of 6216 m². The average specific heat demand is 186 kWh/(m²*a). The system comprises of a heat generator, a buffer tank, and proportional-integral-derivative controller (PID controller). We are not simulating piping networks and the losses associated.

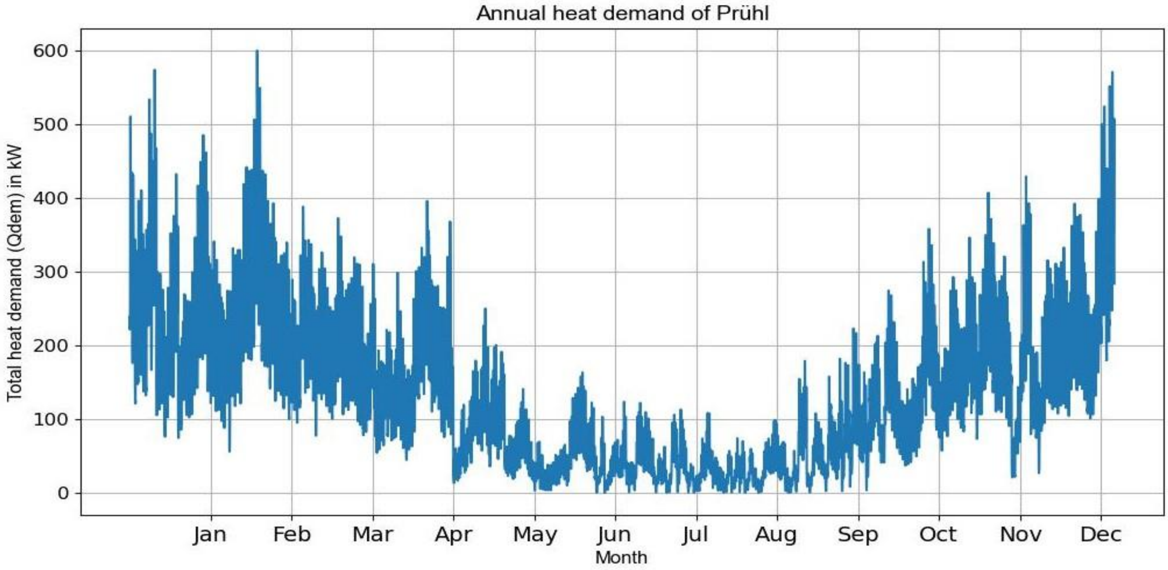

Figure 2. *Annual heat demand of Prühl.*

3.1 Scenario 0: 80% Gas + 20% Oil (Base scenario)

This scenario simulates a standard model with a 400 kW natural gas boiler and a 100 kW oil boiler combined with a 25 m³ buffer tank. The assessment focuses on the energy efficiency and environmental impact of the system. Total energy consumption (Etot) is recorded at 1285 MWh, with carbon dioxide emissions CO_2 totalling 315,000 kg/a.

3.2 Scenario 1: 100% Biomass (Wood chips)

In this simulation, we implemented a wood chips boiler system with wood pellets as the primary fuel source. The key considerations in designing this system were the selection of appropriate heat generators and dimensioning the buffer tank. Our objective was to achieve optimal performance while ensuring the longevity of the boilers.

Heat Generator Dimensioning: We determined that employing a single boiler would be the most effective configuration. We had to choose between one with a capacity of 350 kW and the other with 500 kW. Both boilers have a thermal efficiency(η) of 75%.

Buffer Tank Dimensioning: We varied the buffer tank sizes to regulate the heat distribution and ensure a stable system. Options included tanks with capacities of 5m³, 10m³, 15m³, 20m³, 25m³, and 30m³, each paired with 350 kW and 500 kW boilers. The critical parameter for dimensioning the buffer tank was Qdef (Heat deficit), 5% of heat demand in this case and the number of start/stop cycles throughout the year to minimize the impact on the boiler's lifespan.

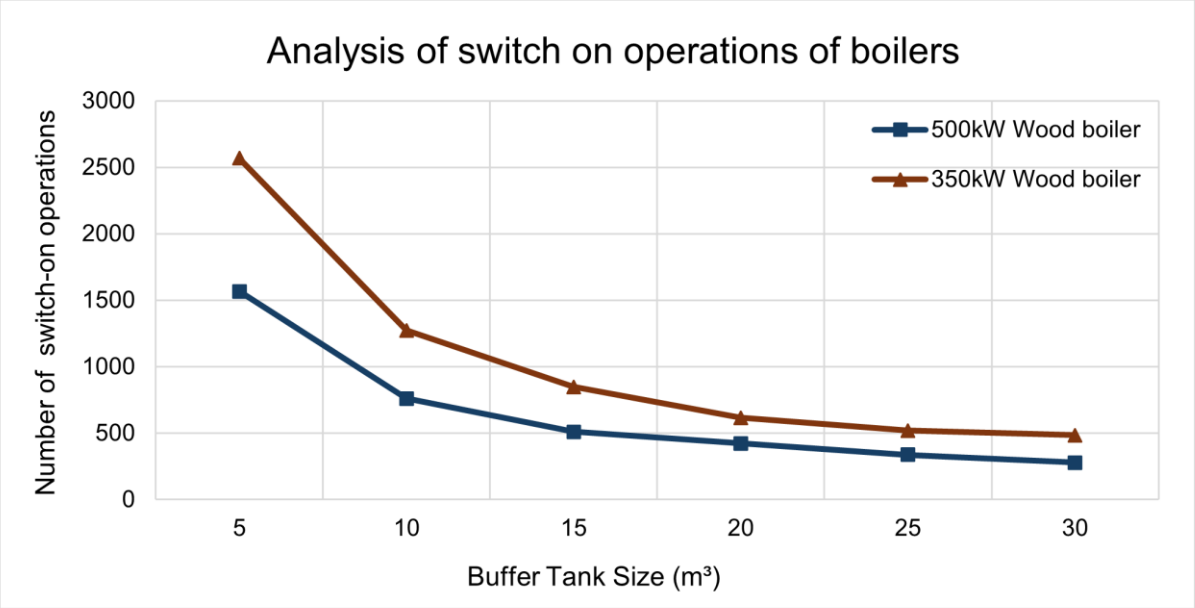

Figure 3. *Analysis of number of switching cycle of boilers.*

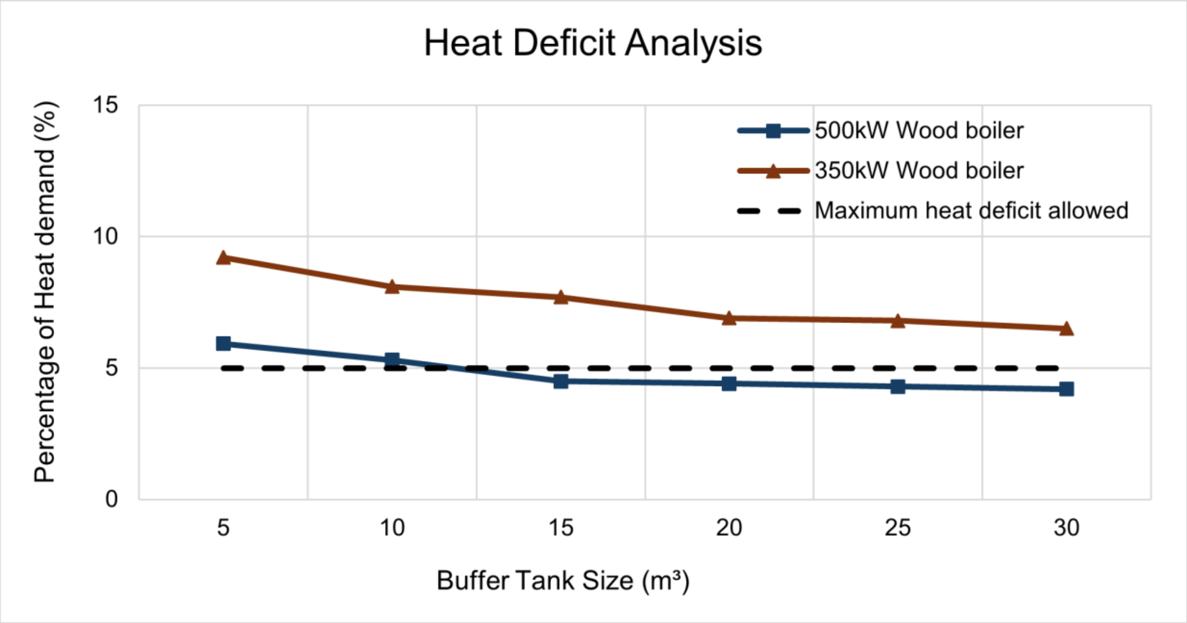

Figure 4. *Analysis of heat deficit of boilers.*

Optimised configuration: We analysed the various combinations and discovered that the most optimised configuration featured a 500 kW boiler paired with a 15m³ buffer tank. In the graph we can also see that this combination exhibited lower start/stop cycles (512) and a reduced Heat deficit of 53 MWh, around 4.5% of the total heat demand, indicating that heating temperature requirements were met consistently throughout the year. The system, configured with the 500 kW boiler and 15m³ buffer tank, had a total firewood consumption of 1505 MWh, furthermore, a carbon emission of 21,600 kg/a which is substantially lower than Scenario 0.

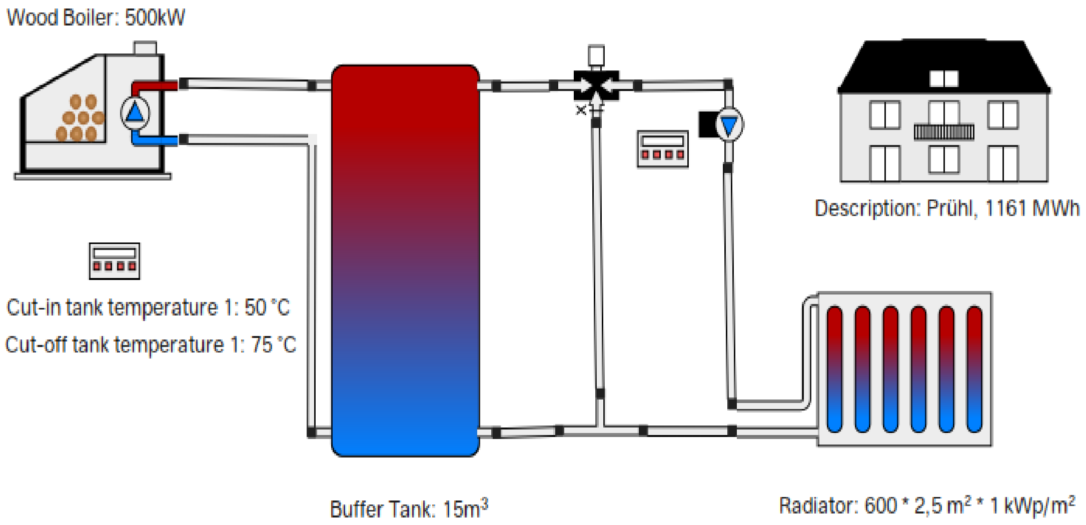

Figure 5. *Polysun® simulation of 500kW wood boiler.*

3.3 Scenario 2: Biomass with Solar Thermal

This scenario investigates integrating solar thermal technology with a wood boiler system. The study encompasses careful dimensioning of the wood boiler, solar thermal collector area, and buffer tank capacity. Optimization strategies are explored to reduce energy consumption, system costs, and carbon emissions.

The wood boiler selected has a 350 kW capacity, chosen for its compatibility with renewable energy integration. Solar thermal technology is dimensioned based on the stagnation period of solar thermal and heat deficit considerations. Stagnation in solar thermal systems occurs when the heat demand is met, and any surplus solar energy is getting wasted. The duration of stagnation is a key consideration in the design of solar thermal systems, influencing their dimensioning and overall performance. Experiments are conducted with solar collector area (600m² & 800m²) and buffer tank capacities (15m³, 20m³, 25m³, 32m³, and 55m³).

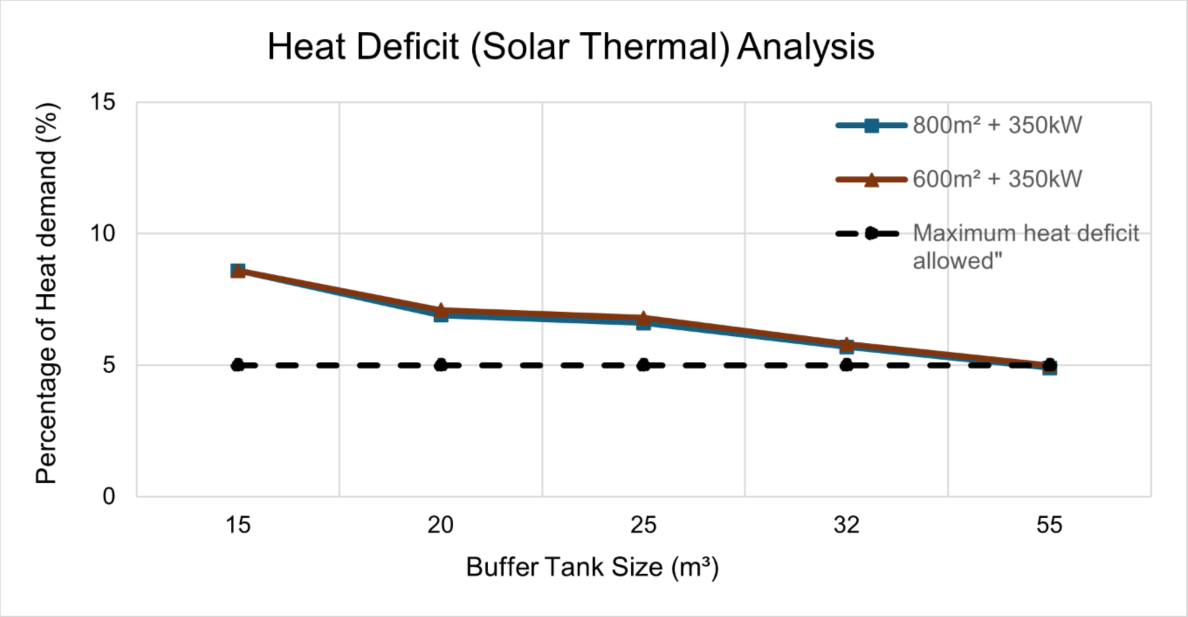

Figure 6. *Analysis of heat deficit with different solar thermal areas.*

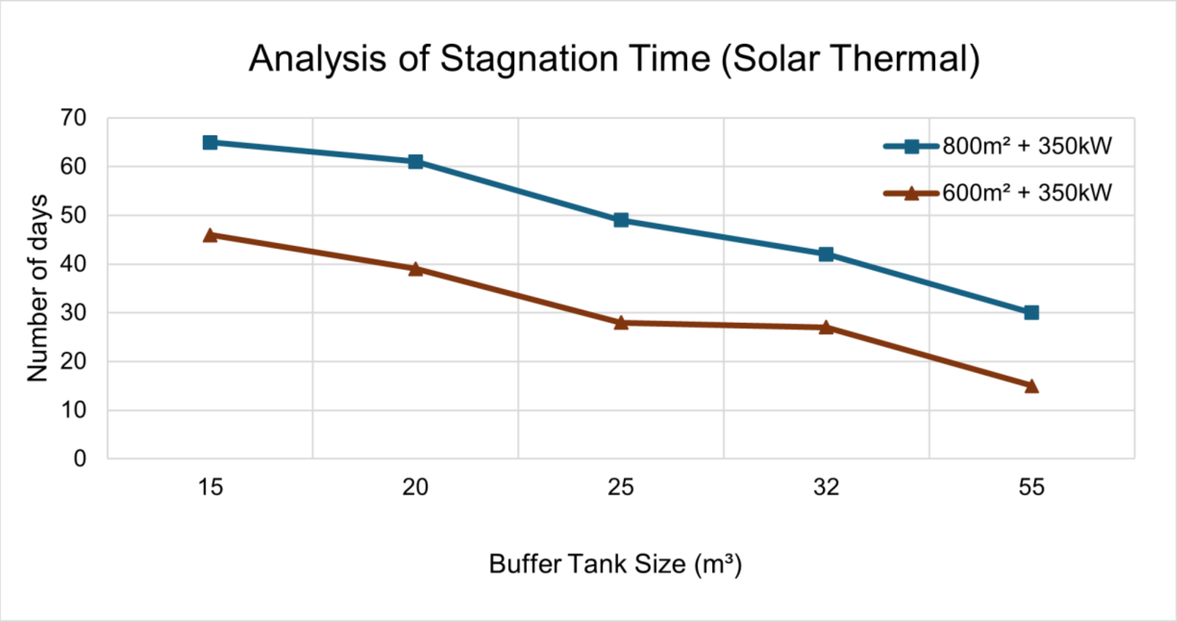

Figure 7. *Analysis of stagnation time in days with different solar thermal areas.*

Analysis of experimentation reveals the optimal buffer tank capacity to be 55m³, considering the heat deficit. Further optimization suggests that reducing the solar collector area to approximately 600m² minimizes the stagnation period from 30 days to 15 days. However, there was very little effect on heat deficit, So, a 350 kW boiler with 600m² and a buffer tank of 55m³ resulted in the optimized system.

The optimized configuration significantly reduces total firewood consumption, reaching 1162 MWh, thereby realizing firewood saving compared to Scenario 1.

The integrated wood boiler and solar thermal system demonstrate a CO_2 emission of 16,700 kg/a, a noteworthy 22.7% reduction in carbon dioxide (CO_2) emissions in comparison with scenario without solar thermal, underscoring the positive environmental impact of the optimized configuration.

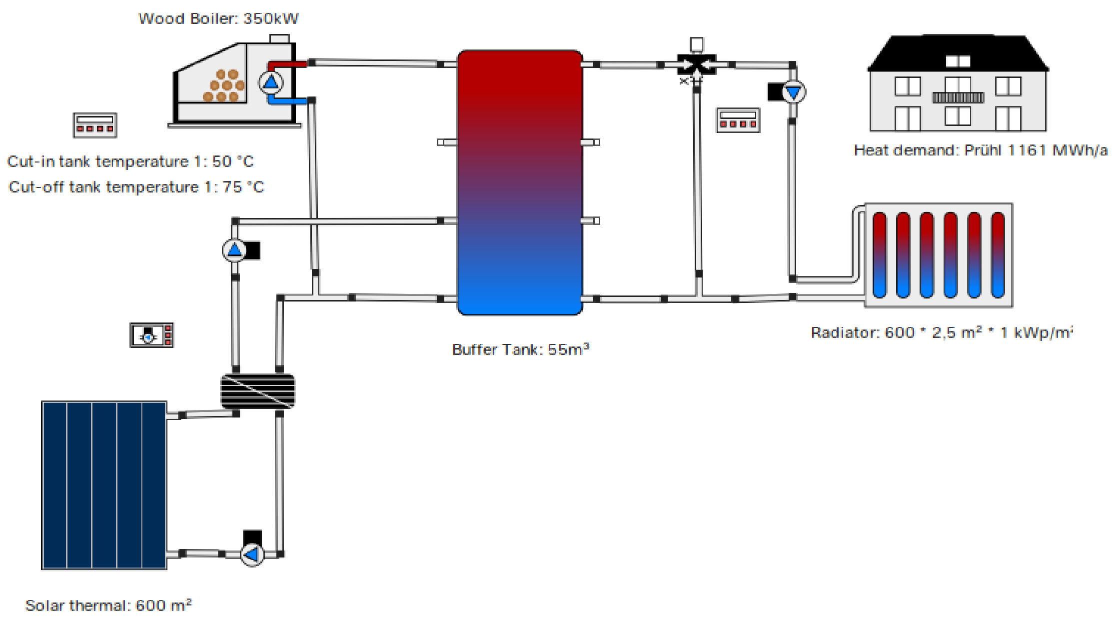

Figure 8. *Polysun® simulation of 350 kW wood boiler with 600m² solar thermal.*

3.4 Scenario 3: Air-Water Heat Pump with Electrical Heat Resistance

This scenario explores the integration of an air-water heat pump utilizing R-407C as the refrigerant. Various heat pump capacities, 150 kW, 200 kW, 250 kW and 300 kW, are examined in conjunction with different buffer tank capacities (10m³, 15m³, 20m³, 25m³, 30m³). Through comprehensive simulations of these combinations, it was determined that the 150 kW and 200 kW heat pump are undersized, while negligible differences were observed between the results of the 250 kW and 300 kW heat pumps. The optimal configuration was identified as a 250 kW heat pump with an annual performance factor (JAZ) of 3.35 combined with a 25m³ buffer tank.

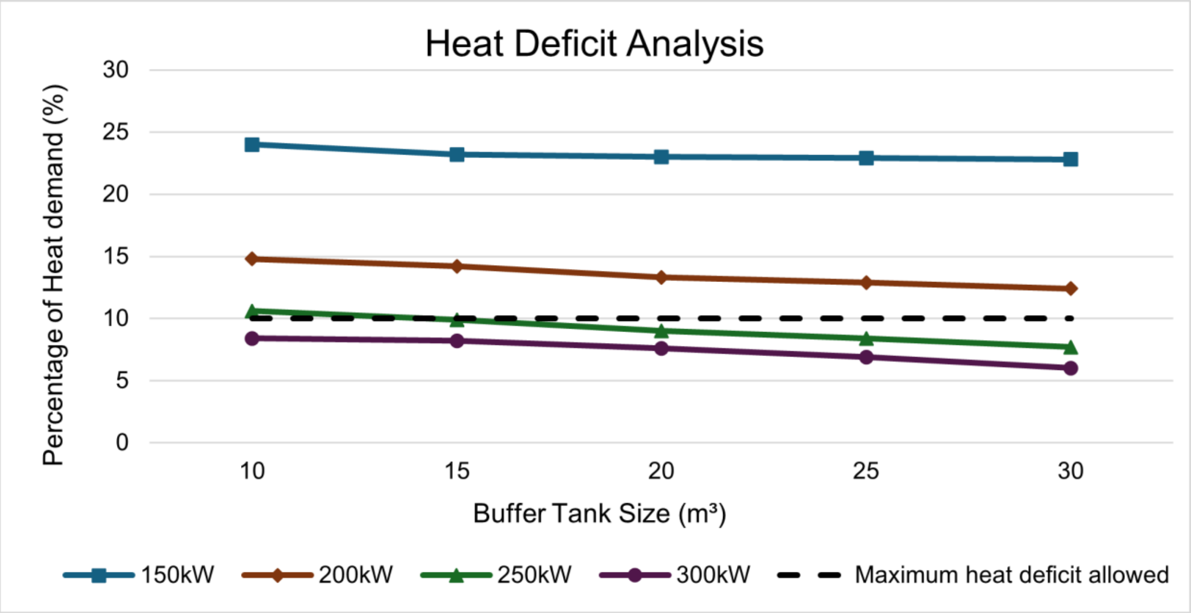

Figure 9. *Analysis of heat deficit with different heat pump sizes.*

In colder months, when external air temperature is insufficient to achieve the desired supply temperatures of around 65 ℃ with the heat pump, supplementary electrical resistance of 20 kW with thermal efficiency(η)=95% is employed to maintain the desired buffer tank temperature. This further decreases the heat deficit. The overall electricity consumption is 339 MWh. The average CO_2eq/kg emission of German electricity demand in year 2023 was 354g CO_2eq/kWh [4] So the total CO_2eq/Year for this scenario is 120,000 kg/a.

3.5 Scenario 4: Geothermal Heat Pump with Electrical Heat Resistance

This scenario represents an analysis of a hybrid heating system integrating a ground source heat pump (GSHP) and an electric heating element. A buffer tank with a 25m³ volume and a ground heat extraction mechanism involving 60 boreholes, each 130 meters deep. The thermal power of the heat pump is 225 kW with an annual performance factor (APF) is 3.72 with an additional 20 kW heating element.

Energy Balance: The hybrid system supplies 85.4% heat with the heat pump and 14.6% heat with the heating element. 60 boreholes, each 130 meters deep, facilitate efficient heat extraction from the earth. Please check with the local authority regarding digging depth. The fluid of the ground loop system is brine. The electric heating element supplements the heat supply when required.

System Performance: The Total electricity consumption is 305 MWh out of which 260 MWh is consumed by the Heat pump and 44 MWh is consumed by electric heating resistance Meanwhile 700 MWh is energy extracted out of the ground.

The CO_2 emissions depend on the electricity source, so the total CO_2eq/Year for this scenario would be 107,900 kg/a. However, with the integration of cleaner energy sources in the grid or the installation of photovoltaics in the system, CO_2 emissions can be reduced substantially

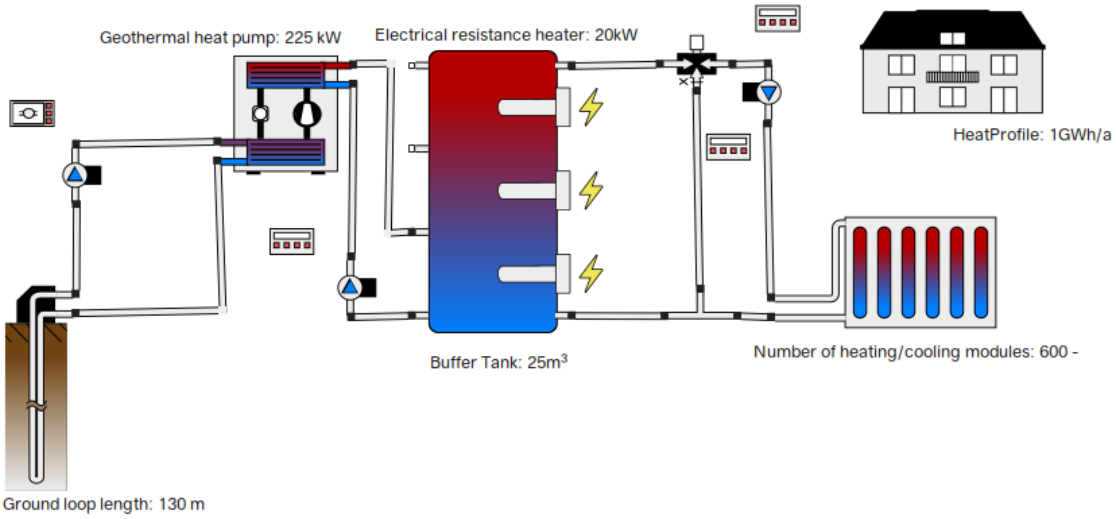

Figure 10. *Polysun® simulation of 225 kW geothermal heat pump.*

3.5 Overview:

Table 1. *Comparison of CO_2eq of the different scenarios.*

Scenario	Technology	CO_2eq/Year	CO_2eq/m^2
0	80% Gas+ 20% Oil	315,000 kg/a	50.60 kg/m²
1	100% Biomass - Wood Boiler	21,600 kg/a	3.47 kg/m²
2	Wood Boiler+ Solar-Thermal	16,700 kg/a	2.75 kg/m²
3	Air-Water Heat Pump + Electrical Resistance Heater	120,000 kg/a	19.30 kg/m²
4	Geothermal Heat Pump + Electrical Resistance Heater	107,900 kg/a	17.35 kg/m²

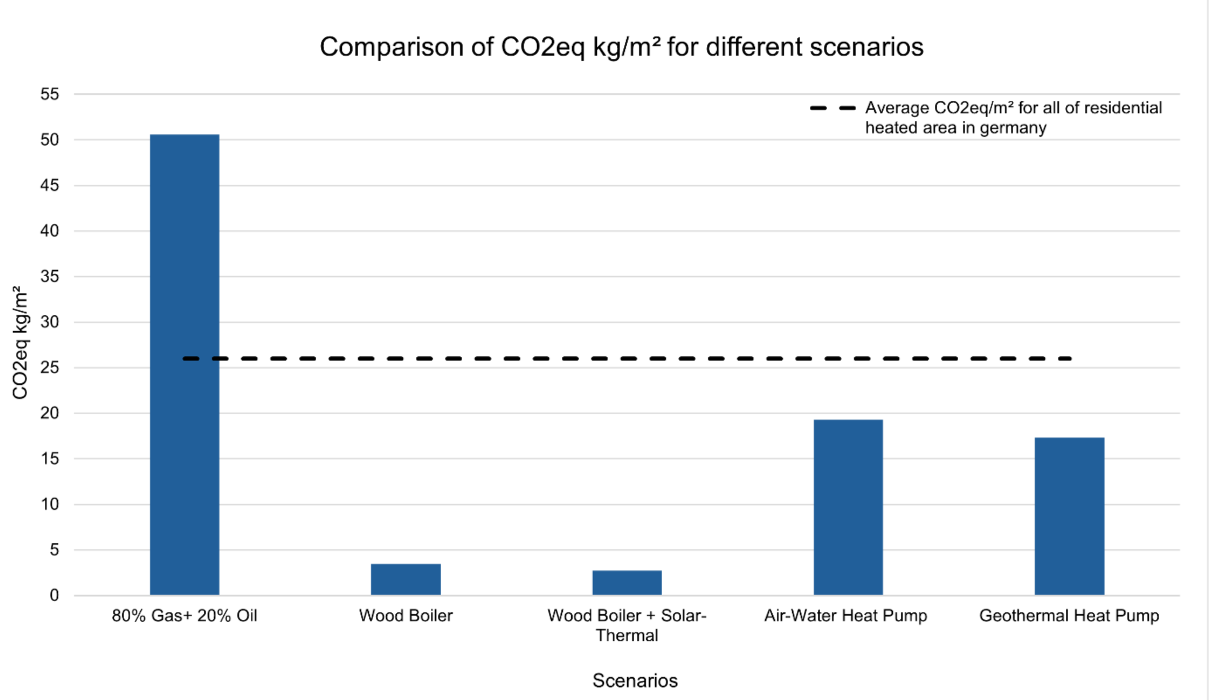

Figure 11. *Comparison of CO2eq kg/m² for different scenarios.*

Heat pumps work using electricity, therefore avoid direct emissions. However, the amount of pollution depends on where the electricity comes from. If the electricity is made from clean sources like wind or solar, the overall pollution is much less. So, using renewable energy with heat pumps will further reduce carbon emssions. Note- The wood is considered as renewable and Polysun® in these simulations only calculates indirect emissions such as transportation, incomplete combustion and harvesting of wood.

4. Conclusion

The study's conclusion presents a set of base parameters and models, empowering rural communities to make informed decisions among a range of heating models. This facilitates the selection of approaches based on feasibility, resource-saving potential, and carbon optimization, specifically for space heating and domestic hot water production. This work promotes energy efficiency and environmental sustainability in rural and similar community settings.

The observed data reveals that biomass coupled with solar thermal exhibits the lowest carbon emissions, while scenarios involving heat pumps display comparatively higher emissions. This disparity is attributed to the carbon footprint associated with the electricity source for heat pumps. Notably, if the electricity supplied to heat pumps is entirely sourced from renewable energy (100% renewable), the system would achieve carbon neutrality.

This study serves as a framework for undertaking similar projects focused on rural district heating. The parameters investigated here establish a foundational baseline for considerations in such endeavors. Our optimization efforts are centered on minimizing carbon emissions, prioritizing environmental concerns without factoring in economic impacts.

Additionally, it is essential to acknowledge that as buildings undergo renovations in the future, the associated heat demand is expected to decrease. Furthermore, establishing a district heat-ing network may attract interest from other buildings not initially included in the plan, prompting the need for future expansion considerations.

5. Outlook

In our current research, we have primarily focused on environmental aspects. However, we acknowledge the significance of incorporating economic considerations. Our ongoing work is dedicated to exploring the economic dimensions of district heating systems, aiming to present a thorough analysis in our upcoming paper.

Data availability statement

Interested researchers can request access to the Polysun® [1] simulations by contacting the corresponding author, Shrey Ayron, (shreyayron@gmail.com). We are committed to transparent research practices and will provide data access upon reasonable request, ensuring compliance with legal and ethical considerations.

Author contributions

According to the CRediT guidelines below are the contributions of each author-

1. Shrey Ayron: Writing-original draft, Conceptualization, Software, Data curation, Investigation, Methodology, Visualization, Formal Analysis
2. Thomas Haupt: Supervision, Project administration, Validation, Writing – review & editing
3. Katharina Herkendell: Supervision, Project administration, Writing – review & editing.
4. Haresh Vaidya: Conceptualization, Supervision, Project administration, Funding acquisition, Resources, Validation, Visualization, Writing – review & editing

Competing interests

The authors declare that they have no competing interests.

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