SIMULATIVE EVALUATION OF HIGH TEMPERATURE VERSUS LOW TEMPERATURE HEATING NETWORKS TO UTILISE WASTE HEAT FROM LARGE FUEL CELLS FOR POWERING DISTRICTS

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Abstract

Fuel cells have emerged as promising combined heat and power systems owing to their environment friendly operation and negligible emissions. Since fuel cells also generate heat as a byproduct during operation, this waste heat could be also used for district heating. In this paper, the bidirectional sector coupling of a high powered fuel cell electric vehicle is simulated in order to power a virtual district in Berlin with electricity and heat. This paper displays the simulated heat demand satisfaction by benchmarking a low temperature heating network versus a high temperature heating network. For the scenarios and the neighbourhood considered in this study, it was found that a single fuel cell vehicle can provide about 90 % of total energy to the considered neighbourhood in case of a high temperature district heating system and 99 % in case of a low temperature district heating system.

1 Introduction

The research and commercialization of heavy-duty vehicles equipped with polymer electrolyte membrane (PEM) fuel cells (FC) are receiving considerable attention in the race to attain carbon neutrality [1, 2]. For the durability of FC in heavy-duty vehicles, the European Commission has established targets of 30,000 operating hours and limiting stack costs to 50 €/kW by 2030 [3].

Operating temperatures for PEM FC stacks range from 50 to 90 °C [4], at the same time allowing waste heat recovery at stack temperatures. The simultaneous generation of heat and electricity make PEM FC an interesting choice for combined heat and power (CHP) applications.

German Aerospace Center's project PEMscale1.5 aims to develop mega-watt scale PEM fuel cells for application in heavy duty mobility like ships, trains, commercial vehicles and airplanes. During idle times, these vehicles can be used as a power source for neighbourhoods. The present paper explores the possibility of integrating a 1.5 MW electric FC that operates at 80 °C and generates roughly 2 MW of waste heat during full load operation as a CHP plant in a residential neighbourhood. The present paper analyses how much and how effectively these fuel cell electric vehicles (FCEV) can deliver heat and electricity to neighbourhoods.

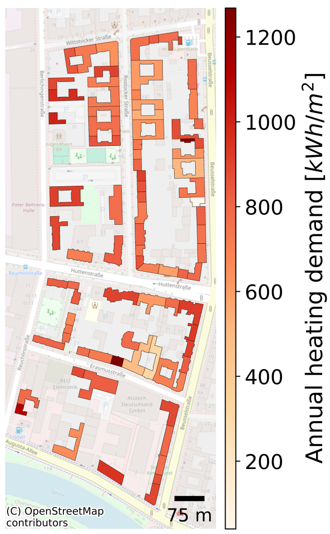

Fig. 1 – Annual heating demands of buildings in the neighbourhood [5, 6] located in Berlin-Moabit © OpenStreetMap contributors [7]

For demonstration, a district located in Berlin-Moabit is used as a representative example neighbourhood. This neighbourhood was chosen because electrical and thermal demands for this neighbourhood were available from a previous study [5, 6] and its proximity to a river bank where a docking station for ships could be located in the future. With the help of annual thermal demands, a virtual district heating system (DHS) was designed to supply this region using DHNx[8]. Two different cases of DHS are compared; (1) High temperature district heating (HTDH) system operating at 80 °C supply temperature and (2) low temperature district heating (LTDH) system operating at 45 °C supply temperature. An energy system model is created in Model Template for Renewable Energy Supply Systems (MTRESS) [9] in order to optimize unit commitment over a selected period of time.These HTDH and LTDH cases are then integrated in the MTRESS model combining FC, heat pump and centralised thermal energy storage to observe the system performance during a peak-winter period of 10 days.

2 Methods

The methodology in this paper can be divided into two parts; firstly the creation and simulation of a district heating network and secondly the modeling and optimisation of an energy system model of the neighbourhood.

2.1 Creation and simulation of district heating network

The electrical and heating load profiles for a neighbourhood located in Moabit-Berlin were available from a previous study [5]. The heat demand results were obtained with the help of aerial imagery, infrared thermography and machine learning [5].

To design a virtual district heating network in order to supply the given neighbourhood, DHNx [8], an open source python package for optimisation of district heating networks was used. Pérez-Iribarren et.al [10] present a novel mixed integer linear programming based approach to design a piping layout for a DHS. The locations of houses, an arbitrarily chosen point for the heating station and piping characteristics were given as input for this model. A constraint was added to restrict the pipe layout to follow streets since laying out pipelines under existing buildings would be impossible. The selected neighbourhood is shown in Fig. 1.

2.1.1 Determining the period of interest: The district heating network (DHN) remains inoperative during summer days and the results would be difficult to visualise for the whole annual duration along with increased simulation time. Instead, it was decided to simulate and study worst-case conditions by selecting a period of 10 consecutive days during winter time in which the demands were at their maximum. Thus, for each day of the year (2023), the demand for that day along with following 9 days was calculated. These "10 day energy demands" are plotted in Fig. 2 using the respective starting days of calculation.

2.1.2 Simulating network losses for HTDH and LTDH: There is no fixed standard for operating temperatures in district heating systems and their classification as low temperature or high temperature networks. Typically, systems operating above 70 °C are labeled as HTDH and systems operating below 50 °C are labeled as LTDH [11]. In this paper, it is assumed that the HTDH operates at 80 °C and LTDH operates at 45 °C.

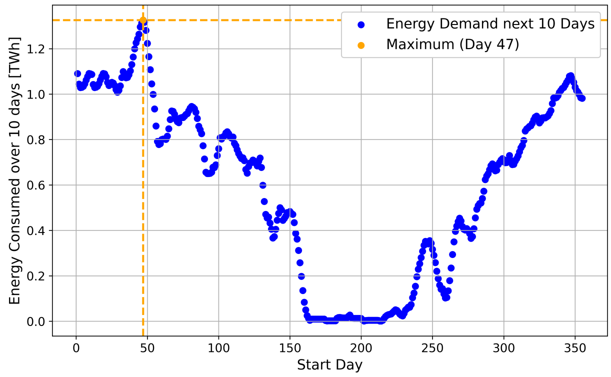

Fig. 2 – Heating demand of a neighbourhood in Berlin-Moabit over a 10 day period starting at 0:00 on the starting day for year 2023

To simulate the network performance, an equivalent pipe approach described in [12] was used. The network was basically reduced to a two pipe system comprising of supply side and return side. In order to represent the network in a simplified manner, two main assumptions were necessary:

1. The supply and return temperatures at every part of the network are the same along with the soil temperature being constant through the entire length of the network.
2. The ratio of outer radius to the inner radius is the same for all sections.

These assumptions simplify the network simulation allowing an estimation of losses with only a small amount of information [12, 13]. Two factors need to be calculated for this approach, the equivalent pipe length and the equivalent heat transfer unit. The equivalent pipe system calculated has the same pressure and thermal losses as the entire district heating network. This method was preferred because it simulates the network performance with minimal network parameters and with a conservative approach. Secondly, the load profiles used in this study are hourly profiles, hence, the use of simplified methods is justified for this time interval.

The equivalent length L_{eq} as described by Heimrath [14] is calculated using equation 1, where L_i is the length of individual pipe segments and m_i is the permissible mass flow in the respective pipe.

$$L_{\text{eq}} = \frac{\sum_i L_i \dot{m}_i}{\sum_i \dot{m}_i} \quad (1)$$

The equivalent heat transfer unit u_{eq} can be calculated by adding that of individual pipes as shown in equation 2 [14].

$$u_{\text{eq}} = \sum_i u_i \quad (2)$$

Having calculated these parameters, the losses in the network (Q_{loss}) were calculated using equation 3 where T_{flow} is the fluid temperature inside the pipe and T_{soil} is the soil temperature surrounding the pipe, respectively [14]. The soil temperature at 1 m depth was used and data from Berlin-Alexanderplatz (nearest) measuring station was used as reference [15].

$$Q_{\text{loss}} = U_{\text{eq}} L_{\text{eq}} (T_{flow} - T_{soil}) \quad (3)$$

2.1.3 Modeling and optimisation of an energy system model of the neighbourhood: To study the energy system performance during worst-winter conditions and to analyse demand satisfaction of the district, it was important to create a mathematical model of the energy system. In this paper, MTRESS [9], a generic model for oemof.solph [16, 17] that provides a variety of possible technology combinations for energy supply systems was used. In MTRESS, arbitrary costs are assigned to energy flows and a mixed integer linear programming problem is formulated and solved in order to determine optimum energy flows.

Fig. 3 shows the components considered in the energy system modelled in MTRESS. The 1.5 MW FC of the FCEV acts as a combined heat and power plant with full load electrical efficiency of 36 % and thermal efficiency of 50 %. It was assumed that there is a centralised heat storage and a centralised heat pump to provide some flexibility in supplying residual heating demand. The neighbourhood is considered as a single entity having time series electrical and thermal demands. The pumping power required to operate the DHS was not considered in this simulation. The costs for grid import and grid export were 0.70 and 0.65 €/kWh respectively. When there was excess production of electricity, it could be exported to the grid, but at a lower price. For hydrogen supply to the FC, a gas grid was assumed with an arbitrary price of 5 €/kg. This was chosen to simulate low cost of hydrogen in future and cost analysis was not the primary objective. Two cases of thermal demands were taken into consideration, one with HTDH and one with LTDH.

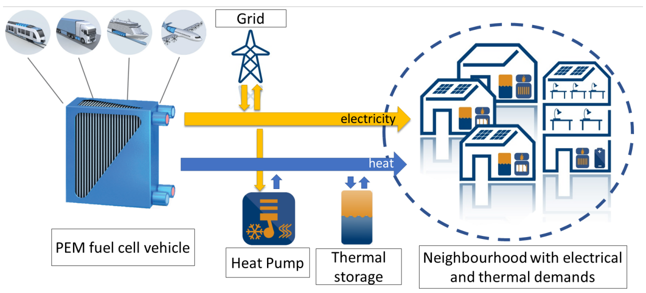

Fig. 3 – Representation of components used in energy system model

3 Results and Discussion

In the first part of this section, the results obtained from simulation of the district heating network scenarios are discussed and the results from the energy modeling are presented in the second part.

3.1 Simulation of a district heating network

Creation of a DHS involves selection of pipes and their layout to supply every consumer in the neighbourhood. The optimization library of DHNx assists in determining the cost-optimal topology and dimensioning of the DHS, considering heat supply plant locations, piping networks and consumer positions. To create a virtual district heating network, locations of consumers (buildings), heating station and pipe parameters had to be given as input parameters. Fig. 4(a) shows a preliminary heating network created in DHNx before optimization [8]. Table 1 gives pipe parameters used as input parameters in DHNx [18]. Fig. 4(b) shows the optimised network to minimize costs along with selected pipe characteristics.

Table 1 Pipe characteristics pre-insulated rigid steel pipes [18]

Pipe type	Loss [W/m]	Maximum capacity[kW]	Variable costs[€/kW]	Fix costs[€]
DN-20	0.284	47	282.5	423.7
DN-25	0.342	54	293.1	439.6
DN-40	0.403	87	324.9	487.4
DN-63	0.527	176	373.7	560.6
DN-80	0.547	298	409.8	614.8
DN-100	0.576	552	452.3	678.4
DN-150	0.777	2576	558.4	837.7
DN-250	0.820	56065	770.7	1156.1

The daily space heating demands and the losses incurred when provided through a district heating network are shown in Fig. 5. The blue coloured bars represent the heating demands of the neighbourhood while the orange and green bars represent network losses incurred in HTDH and LTDH scenarios, respectively. In each case, the total energy provided to the DHS can be obtained by summing up the demands and losses. From equation 3, it can be deduced that the network losses are dependant on the supply temperature of the fluid when the soil temperature is equal.

3.2 Energy demand analysis

Fig. 6 shows the sources and amount of the thermal power composition sent to the neighbourhood. It can be seen that the waste heat alone from the PEM FC is not sufficient to supply the entire neighbourhood. The remaining energy is obtained mainly from the heat pump and to a lesser extent from the thermal storage. Fig. 6 gives a first impression that thermal storages might not play a major role in the energy system. However, in this case, the thermal storage shaves off peak loads from the heat pump, thus reducing the heat pump size. Secondly, the

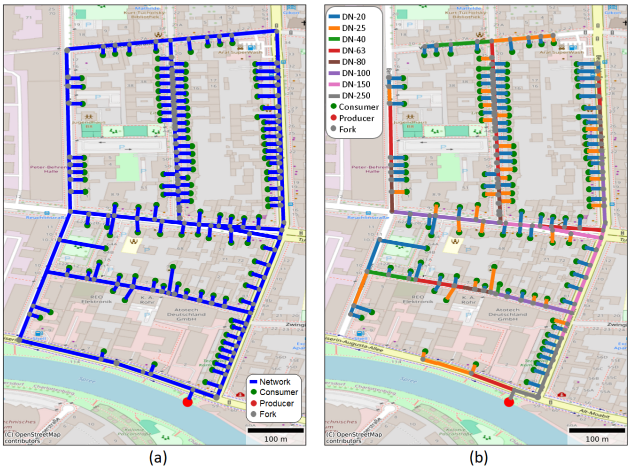

Fig. 4 – Simulated virtual district heating network to provide heat for the buildings. (a) Network before optimisation and (b) network after optimisation using DHNx package [8]. The Diameter Nominal (DN) of the pipes are shown. Producer is the fuel cell electric vehicle (FCEV). Consumer are the buildings. © OpenStreetMap contributors [7]

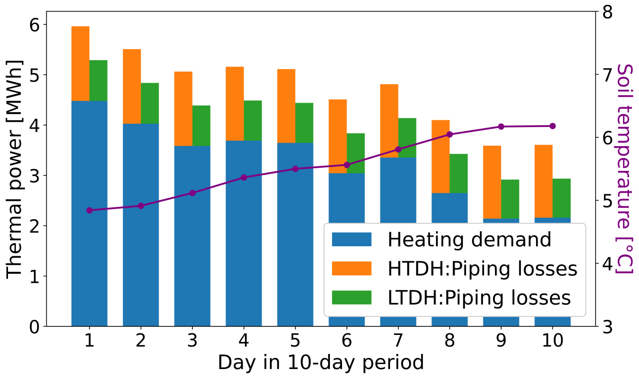

Fig. 5 – Daily average heating demand of the neighbourhood in Berlin-Moabit. LTDH, low temperature district heating. HTDH, high temperature district heating

size of the thermal storage and assumed boundary conditions also play a major role. For the sake of a conservative approach, the thermal storage of 22 m^3 was considered and assumed to begin at zero energy content on the first day which might not always hold true.

A similar trend is observed in the case of thermal power composition dispatch with LTDH, as shown in Fig. 7. The major difference is the decrease in power requirement which results from lower losses in the network.

To compare the performance of HTDH and LTDH scenarios over the 10 day interval, thermal dispatch results from both scenarios have been summarised in the form of an annular chart in Fig. 8. The share of direct utilisation of waste heat from the FC is reduced from 408.1 MWh using HTDH to 309.3 MWh in the case of LTDH. This is because the full load operation of the FC

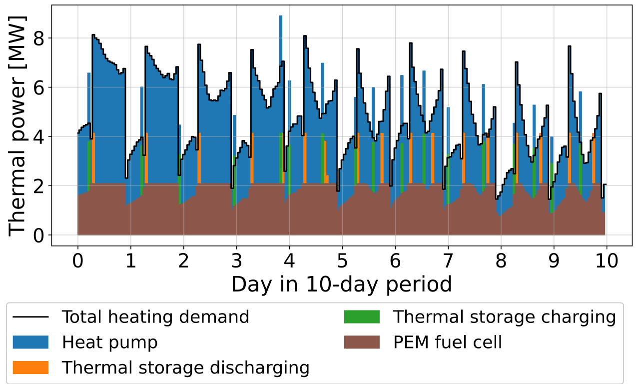

Fig. 6 – Heating demand dispatch and heating sources for the neighbourhood during 10 day period using a high temperature district heating (HTDH)

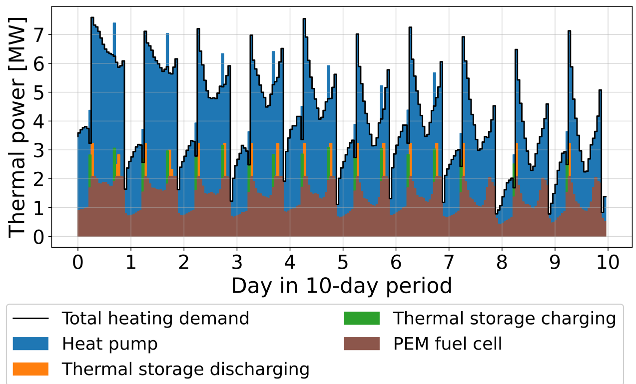

Fig. 7 – LTDH: Heating demand dispatch and heating sources for the neighbourhood during 10 day period using a low temperature district heating (LTDH)

is reduced when compared with HTDH as also observed from Fig. 7.

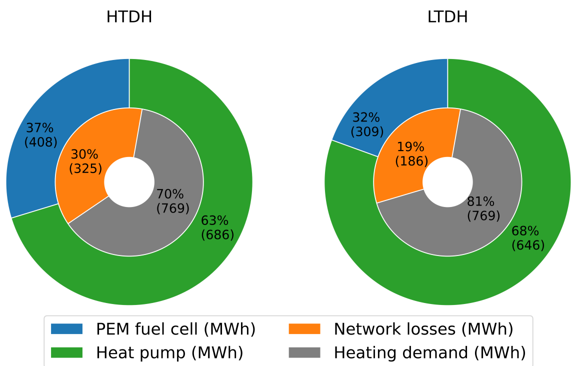

Fig. 8 – Summarised thermal power dispatch over considered 10 day period in the neighbourhood comparing HTDH and LTDH cases

The thermal energy lost from the network to surroundings is reduced to 19 % in the case of LTDH as compared to 27 % in the case of HTDH.

The electricity dispatch results for the neighbourhood using LTDH or HTDH are shown in Fig. 9 and Fig. 10, respectively. To avoid repetitive figures and for better understanding, consumers i.e. the components requiring power are shown along the positive y-axis and producers i.e. components producing power are shown along the negative y-axis in both Fig. 9 with HTDH and Fig. 10 with LTDH:

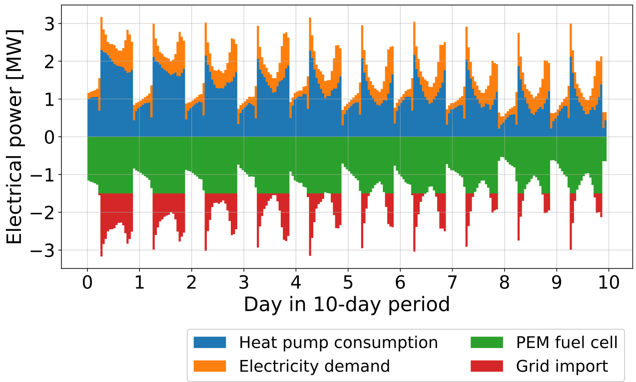

Fig. 9 – HTDH: Electrical power consumption and production in the neighbourhood of Berlin-Moabit during 10 day period (positive values show consumers and negative values show producers)

In Fig. 9, the PEM FC generates electricity and is capped by it's maximum electrical output of 1.5 MW. The surplus energy required is imported from the grid. The electricity produced is shared between heat pump and the electrical demands of the neighbourhood. The presented curves appear like a step wise function because the demand data was only available with a one hour resolution for the duration under consideration.

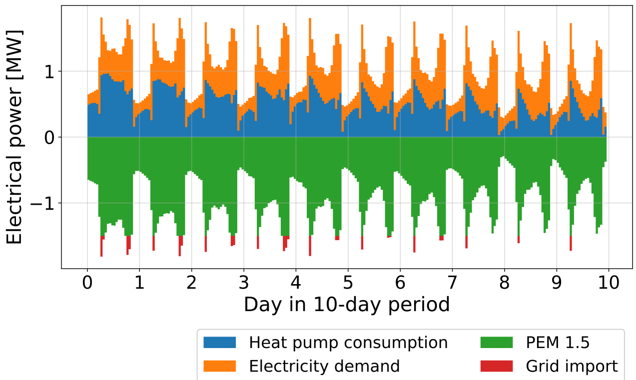

Fig. 10 –LTDH: Electrical power consumption and production in the neighbourhood during 10 day period (positive values show consumers and negative values show producers)

From Fig. 10, it can be seen that in case of LTDH, the electricity imported form the grid is significantly reduced. This is because of lesser thermal demands of the neighbourhood as seen in Fig. 7.

The electricity production and consumption for the energy system has been summarised in Table 2. The electricity imported from the grid reduces greatly (94.3 %) in case of LTDH compared to HTDH. This means that the energy system achieves more independence from the grid in case of LTDH network.

Table 2 Electricity production and consumption for various components in scenario with HTDH or LTDH

Component	HTDH [MWh]	LTDH [MWh]	LTDH vs. HTDH
Fuel cell	279.4	217.4	-22.2%
Grid Import	76.1	4.4	-94.3%
Heat pump	252.2	118.3	-53.1%
Demand	103.5	103.5	0%

In addition, the electricity consumption by the heat pump is reduced by 53 % in case of LTDH compared to HTDH, even though the heat pump supplies a greater fraction of the heat demand. Two factors contribute to this observation. Firstly, the losses are reduced which means a reduction in net supplied energy and secondly, there is also a significant improvement in the coefficient of performance (COP) of the heat pump because of a reduced temperature lift required in case of LTDH.

4 Summary

The integration of a high-powered FCEV and its contribution as a combined heat and power plant for a neighbourhood have been discussed in this paper for low temperature and high temperature heating networks. Considering both cases, it can be concluded that these FCEV under development have a promising potential to substitute traditional fossil burning CHP systems in case of emergencies or high price situations.

LTDH networks offer significant advantages over traditional HTDH networks. The thermal losses in LTDH piping networks are lower because of lower operating temperatures and in the case of the considered system in this study, they were lesser by 42.8 % on average compared to HTDH. Another advantage of LTDH is better energy efficiency when integrating heat pumps because their COP is greatly dependant on temperature lift. Also for thermal storages the energy losses are less due to lower temperatures used in LTDH, however, the energy stored per unit volume is reduced for low temperature storages.

In the considered scenario and neighbourhood in this study, it was found that a single FC can provide about 90 % total energy to the considered neighbourhood in case of HTDH and 99 % in case of LTDH. These type of e.g. 1.5 MW FC will be used for heavy duty mobility applications like ships, aeroplanes, cargo trucks etc. and have the potential to act as stand-by CHP units for neighbourhoods.

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6 CRediT authorship contribution statement

Writing – original draft: NG. Writing - Review and Editing: NR and BS. Data curation: NG and CM. Methodology: NG and NR. Supervision: NR and MK. Project administration, Conceptualization: MK, MV, AD. Acronyms: Nachiket Gaikwad(NG), Nies Reininghaus(NR), Carlos Muñoz(CM), Michael Kroener(MK), Barbara Satola(BS), Martin Vehse(MV), Alexander Dyck(AD).

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