19. Status-Seminar «Forschen für den Bau im Kontext von Energie und Umwelt»

Modelling the Suurstoffi district based on monitored data to analyse future scenarios for energy self-sufficiency

Ashreeta Prasanna[1], Nadège Vetterli[2], Viktor Dorer[1], Matthias Sulzer[2]

1: Empa, Urban Energy Systems Laboratory, Überlandstrasse 129, 8600 Dübendorf
2: HSLU-ZIG, Technikumstrasse 21, 6048 Horw

A. Prasanna, ashreeta.prasanna@empa.ch, N. Vetterli, nadege.vetterli@hslu.ch

Zusammenfassung Résumé Abstract

Ein Niedrigenergiequartier in der Schweiz, welches mit Wärme und Kälte aus einem Erdwärmespeicher gespeist wird, wurde zur Optimierung dessen Betriebs modelliert. Insbesondere soll damit eine Maximierung der Eigenversorgung erzielt werden. Die im Erdreich gespeicherte Wärme wird mittels Wärmepumpen in Heizwärme und Warmwasser umgewandelt. Den Strom beziehen diese hauptsächlich aus den lokalen Photovoltaik (PV)- und Hybrid (PVT)-Solaranlagen. Im Modell wurden die bestehenden Gebäude durch dezentrale Umwälzpumpen mit dem bidirektionalen Netz verbunden und Monitoring-Werte zum Wärme- und Kühlbedarf als Inputdaten verwendet. Erste Optimierungen zur Minimierung der Treibhausgasemissionen des bestehenden Areals wurden bereits durchgeführt. Die Ergebnisse wurden zur Kalibrierung des Modells mit den Monitoring-Daten des Strombedarfs für die Umwälz- und Wärmepumpen verglichen. In einem zweiten Schritt wurden im Modell weitere Arealgebäude eingefügt, und ferner zusätzliche oder ergänzende Technologien wie Strom- und Wärmespeicherung geprüft (PV und Batterien, Ersatz von PV durch PVT). Die Ergebnisse liefern nützliche Hinweise für die weitere Planung des Areals, zu möglichen Betriebsszenarien sowie zur Rentabilität und Amortisation der verschiedenen Optionen.

A low energy district in Switzerland whose heating and cooling demand are supplied to a large extent by heat stored in borehole fields is analysed in this publication. Heat pumps that convert heat from the ground storage into floor heating and domestic hot water are mainly powered by electricity produced by conventional photovoltaic (PV) and hybrid (PVT) solar panels. In order to better understand the system operation, an optimisation model was implemented, in which buildings are connected to a network with bidirectional flows and decentralised pumps. Monitoring data for heating, cooling and domestic hot water demands were used as an input to this model and a first optimisation to minimise carbon emissions was performed. The model was calibrated by comparing the calculated electricity demand for heat pumps and network pumps with measured data. In a second step, additional buildings within the district and complementary or alternative technology options as heat and electricity storage (PV and battery, replacement of PV with PVT) were included in the model. The results provide insights on the extent into which the system design can be improved, to help the development of future operation scenarios and point out the benefits and drawbacks of the various options.

1. Introduction

1.1 The Suurstoffi project

The Suurstoffi district situated in Risch Rotkreuz consists of the “*Westareal*” and the “*Ostareal*” (figure 1), which include both commercial and residential buildings. The buildings in the *Westareal* were completed in 2012/2013 and have been in operation in succession once their construction was completed. The *Ostareal* which consists of BFA, BFB, BFC is still under construction. The district heating and cooling network supplying this site has been in operation since 2012. This ‘Anergienetz’ or low temperature network (LTN) connects about 100’000 m² of residential, commercial and industrial buildings with a seasonal ground storage consisting of 215 existing boreholes (150m deep). Once the construction of the entire district will be completed in 2020, the *Westareal* and *Ostareal* will cover approximately 165’000 m² floor space (1500 residents, 2000 students and 2500 workplaces) and will be supplied by 215 boreholes of 150m depth and 840 boreholes of 280m depth.

In this paper, only the building sites BF2, BF5 and BF3 are considered. This is because electricity and heat demand data for these specific sites is monitored and analysis of monitoring data is published in freely accessible monitoring and sustainability reports [1,2,3]. This monitoring data is used as a basis for the present research and is used to develop and verify an optimisation model. This study only includes energy use for the operation of the building facilities for heating, ventilation and air conditioning (HVAC), i.e., household electricity consumption is not considered within the model boundary.

Heating and domestic hot water are produced via decentralised heat pumps connected to the ground storage via the LTN. The waste heat from the freecooling in the buildings is injected into the LTN for the regeneration of the ground storage. The conventional and hybrid photovoltaic panels installed on the roofs should cover the entire electricity demand for the building operation (for the heat pumps, circulating pumps and heating bands) as well as supply additional heat for the regeneration of the ground storage. This should guarantee low non-renewable primary energy consumption and, as much as possible, a greenhouse gas emission free operation.

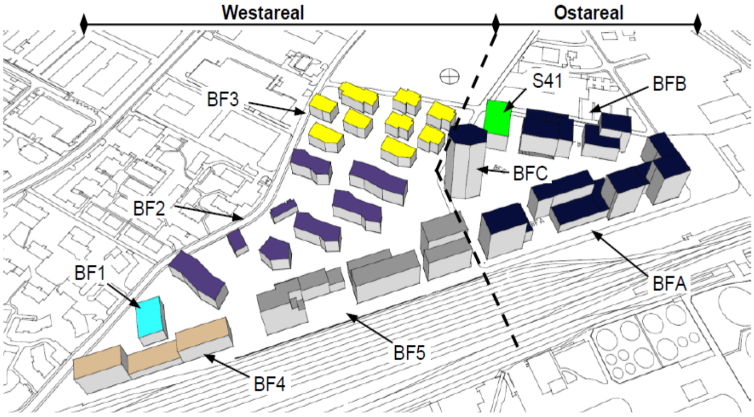

Figure 1. Overview of the Suurstoffi district and the different building sites (source: Hans Abicht AG)

1.2 Monitoring

In order to verify the objectives, the network “Suurstoffi” is being measured for at least five years. Each heat and power flux as well as temperature changes are measured every 15 minutes resulting in a total of about 400 data points over the building sites BF2 and BF5 currently in operation. The Lucerne University of Applied Sciences has been analysing the measured data since 2012 [1, 2].

Analysis of the monitoring data ensures sustainable operation of the network and system. The analysis of variation in borehole temperature provides a better understanding of their performance. In 2013, undercooling (drop in the mean temperature of the boreholes) was identified through data monitoring and appropriate measures were implemented to prevent network undercooling in winter

2014. These measures included additional heat supplied to the network by a temporary wood-fired boiler (pellet) in combination with electric heating for domestic hot water.

Monitoring data of heating demand was also found to be twice higher than calculations made during planning and design, i.e. large performance gap. Similarly, freecooling was also much lower than calculated. For the buildings under construction, new technologies and systems are planned and these must be tested in terms of effectiveness, efficiency, flexibility and reliability. The monitoring data therefore continues to be used as a basis for modelling and simulation and is essential not only to improve the accuracy of the models through calibration but also to optimize system operation [3].

1.3 Methodology

The methodology followed in this research work is described in figure 2 and a detailed description of the model is found in section 2. The model was initially run with monitoring data for buildings in BF2 and BF5. The model was calibrated by comparing results obtained for carbon optimisation for the electricity consumption of heat pumps and network pumps to monitoring data. The electrical production of the photovoltaic panels was also compared to complete the verification of the model describing BF2 and BF5. Additional buildings in building site 3 (BF3) were then included in the verified model. The demand loads of BF3 were based on the load profile of buildings in BF2 (similar sized residential buildings) and assumptions based on SIA standards. Since no measured data is available for BF3 yet, the results for this base case model were verified by comparison with design calculations. The model consisting of buildings in BF2, BF5 and BF3 and all other equipment and storage connected to the LTN was considered as the base case for subsequent scenario analysis.

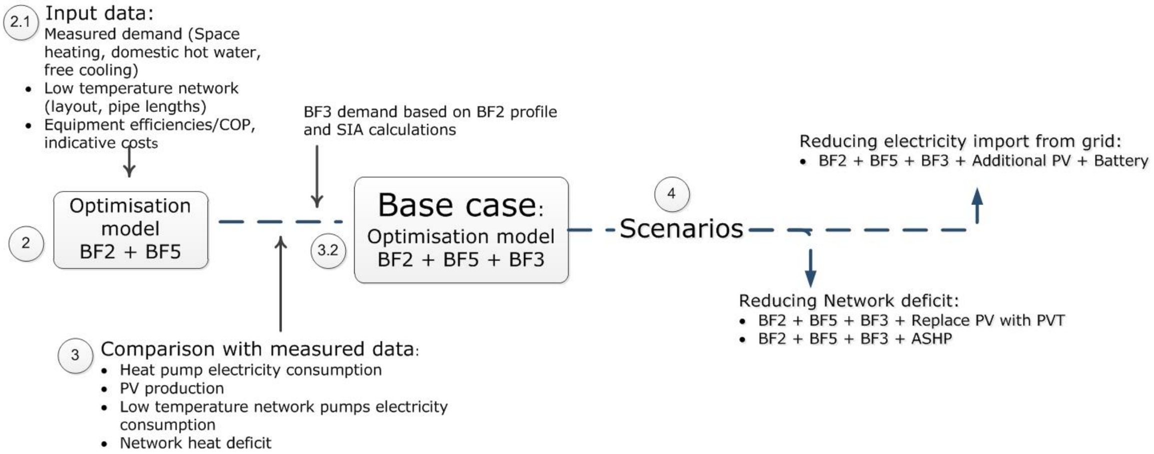

Figure 2. Methodology and sections in this paper where topics are elaborated further

2. Description of the optimisation model and boundary conditions

In this research, the Suurstoffi system is analysed from the perspective of optimisation modelling. Subsequently, it is planned to further analyse initial results by developing a simulation model where subsystems are described in detail and nonlinear operation of the system is taken into account.

Optimisation modelling and simulation use very different approaches to understand system dynamics. In the optimisation model described here the entire system is formulated as a mixed-integer linear problem (MILP). The mathematical description of subsystems in the model is based on earlier work by Morvaj, Evins and Orehounig [4, 5, 6]. A MILP consists of linear equations with parameters (inputs varying over time or fixed value), variables and constraints (system requirements, energy balance for each time step). An objective function is defined, in this case, minimisation of total carbon emissions (described in section 2.2). The optimisation model was implemented in AIMMS, a software tool for optimisation modelling using the solver IBM CPLEX. The CPLEX solver finds the optimum solution for the objective function, subject to defined constraints.

The building level model consists of the configuration shown in figure 3. Each building is modelled with the same configuration - a low temperature heat pump (HP_{LT}) and a high temperature heat pump (HP_{HT}). Heat storage is included in each building for storage of heated water from PVT panels and/or waste heat from freecooling of buildings in summer. The main difference between the model setup and the actual situation is this additional storage tank where heat from freecooling can be stored in the short term for local use within the building. In the optimisation model, the flow direction along a pipeline is constrained to be fixed during each time step, but can switch between different time steps. This requires an energy balance for each time step at each building node. It is assumed that this energy balance between heat demand (domestic hot water) and heat production (waste heat from freecooling) occurs within a building storage tank, and thus this additional storage tank is included in the building model.

Buildings in BF2 and BF5 include PV panels, while buildings in BF3 include PVT panels. The network model includes accurate pipe lengths and the three entry points to the borehole storage (BHS). The losses in thermal energy in the network are calculated as a function of total energy transmitted though the section of the pipe and the pipe length. Bidirectional flow; i.e. changes in the direction of fluid flow in a pipe over time is considered and flow direction along each pipe for each time step is a variable. Mass balance, temperature and pressure drop in the network are not modelled since they require non-linear formulations which cannot be described within the current framework.

The maximum charge and discharge rate of the borehole field is limited by the flow rate within boreholes (1.8 m^3/h). This is taken into account in the model by imposing constraints on the maximum charge and discharge rate of the borehole field.

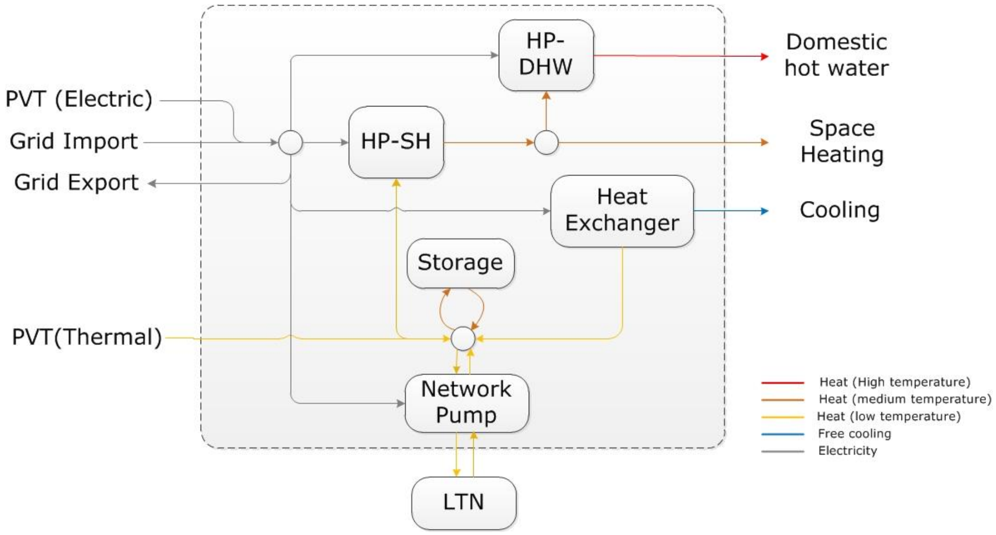

Figure 3. Description of building level model

2.1 Input data

Measured hourly demand for the time period 1 October 2013 to 30 September 2014 was used as an input to the model. In order to decrease the computational load and solving time, the measured loads for 365 days were reduced to 12 days (288 hours); i.e., one representative day per month. Another reason for reducing the input data to 12 days was the lack of measured data for certain time periods (temporary breakdown of measurement sensors). Instead of creating demand profiles for the missing periods, an average day profile was selected and then multiplied by 30 or 31 to calculate the total demand for the month. However, in some cases it was not possible to find a day profile which could precisely match the monthly average. An example of the error caused due to data reduction can be observed in the comparison of the results with inputs for freecooling and solar radiation (PV production), which were highly variable during summer months. The comparison of the total annual heating, cooling and domestic hot water demand for BF2 and BF5 to the respective measured values is shown in figure 4a.

Assumed values for installed capacity, cost and efficiency for the different cases are given in table 1.

Additional assumptions include the carbon factor of electricity imported from the grid (0.038 kg CO_2/kWh), the cost of electricity purchased from grid (0.18 CHF/kWh), the cost of electricity sold to grid (0 CHF/kWh) and the project lifetime of 20 years.

		Technology	Efficiency/COP	Total capacity	Cost
Initial case (BF2 + BF5)	Buildings	HP$_{LT}$	Combined COP 4 - 5.5	1354 kW	1000 CHF/kW
		HP$_{HT}$		699 kW	1200 CHF/kW
		PV	Efficiency:18%	2651 m^2	500 CHF/m^2
		Heat exchanger	Efficiency: 80%		1500 CHF/kW
		Building storage tank	Charging efficiency:: 98% Discharging efficiency:: 98%	Max charging and discharging rate: 80% 2000-4000 lt (100-150 kW) per building	50 CHF/kW
		Network pumps	Efficiency: 60%		500 CHF/kW
	Network	BHS	Charging efficiency: 98%, Discharging efficiency: 98%,	Max charging capacity: 1806 kW/h Max discharging capacity: 1354.5 kW/h Total capacity: 2GW	1000 CHF/kW
		ASHP	COP: 2 - 4.5 (summer)	340 kW	800 CHF/kW
		Pipe network	2% per km		700 CHF/m
BF3	Buildings	PVT	Thermal efficiency: 70% Electrical efficiency: 18%	2900 m^2	1300 CHF/m^2
		HP$_{LT}$	Combined COP 4 - 5.5	419 kW	1000 CHF/kW
		HP$_{HT}$		480 kW	1000 CHF/kW

Table 1 Efficiency, costs and capacities input into the model

2.2 Objective functions

The optimisation model is solved for an objective function to obtain results for variables at each time step. Minimisation of total carbon emissions is used as an objective function in the model. Since the Suurstoffi district is entirely electricity based, the total carbon emissions are equal to the amount of electricity purchased from the grid multiplied by its carbon factor. The electricity produced by the PVT/PV on site is assumed to have zero carbon emissions (equation 1).

$$Carbon_{total} = \sum_i \sum_t (CF_{grid} * P_{grid}) \tag{1}$$

The surplus of electricity delivered to the grid is assumed to have no positive effect on the grid carbon factor. Therefore, we must assume that the renewable energy supplied to the grid does not substitute the high carbon electricity in the grid. This assumption has to be so conservative, because the feed-in is purely stochastic.

For the scenarios' evaluation, a relation between the increase of investment costs required to decrease emissions produced is obtained using the epsilon constraint method, where optimisation for carbon is performed restricting the total investment cost [6].

3. Results

Optimisation results for the initial case (BF2 and BF5) and comparison with measured data are shown in figure 4a and 4b. The model results for BF2 + BF5 have less than 5% error when compared to measured annual values, except for electricity consumption of network pumps and freecooling in BF2. The difference in network pump consumptions is further discussed in section 3.2.

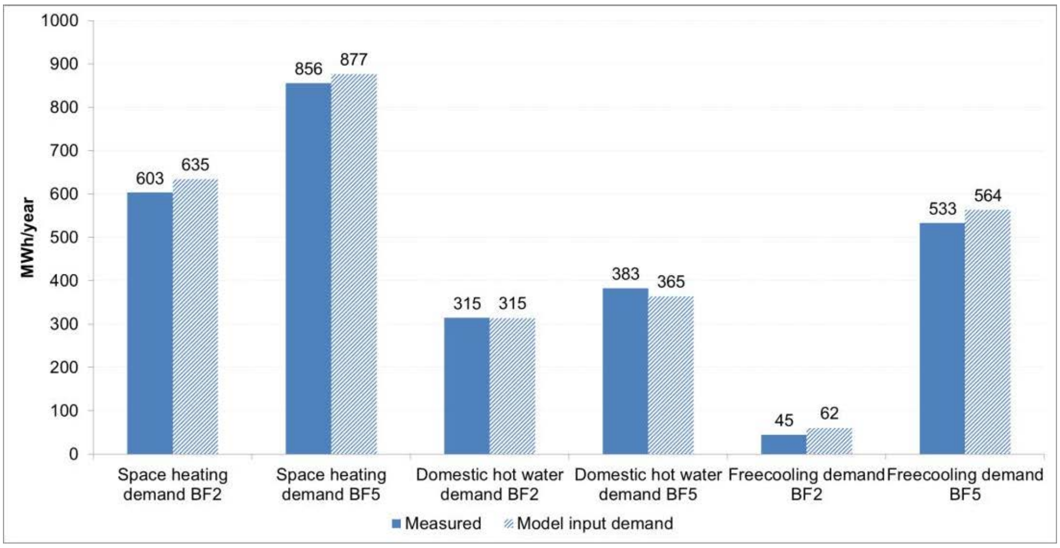

Figure 4a. Comparison of measured demand with model input demand

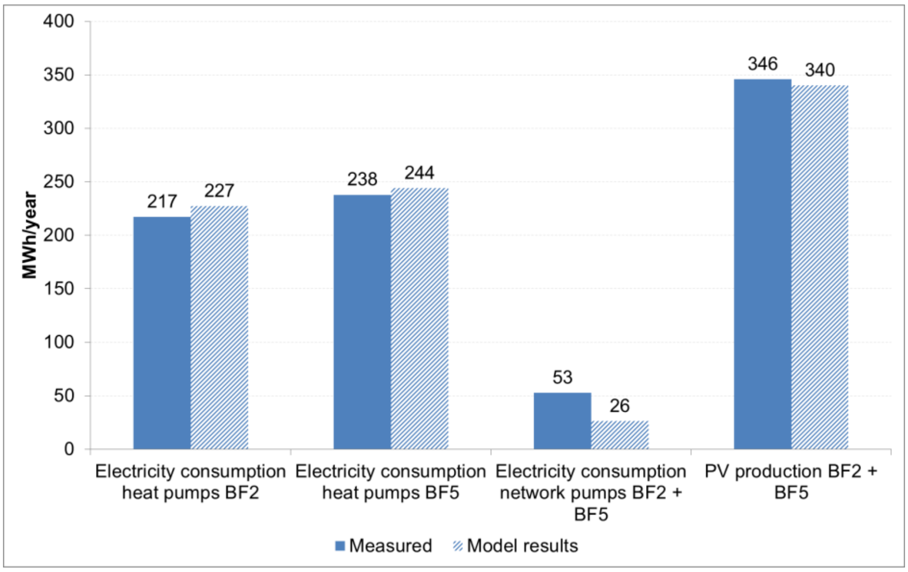

Figure 4b. *Comparison of measured electricity demand with model results*

3.1 Comparison of PV production

The comparison between measured PV production and model results is shown in figure 5. The differences observed are mainly due to the reduction of radiation profiles from 30 days to 1 average day per month. The model results are reasonably close to measured values.

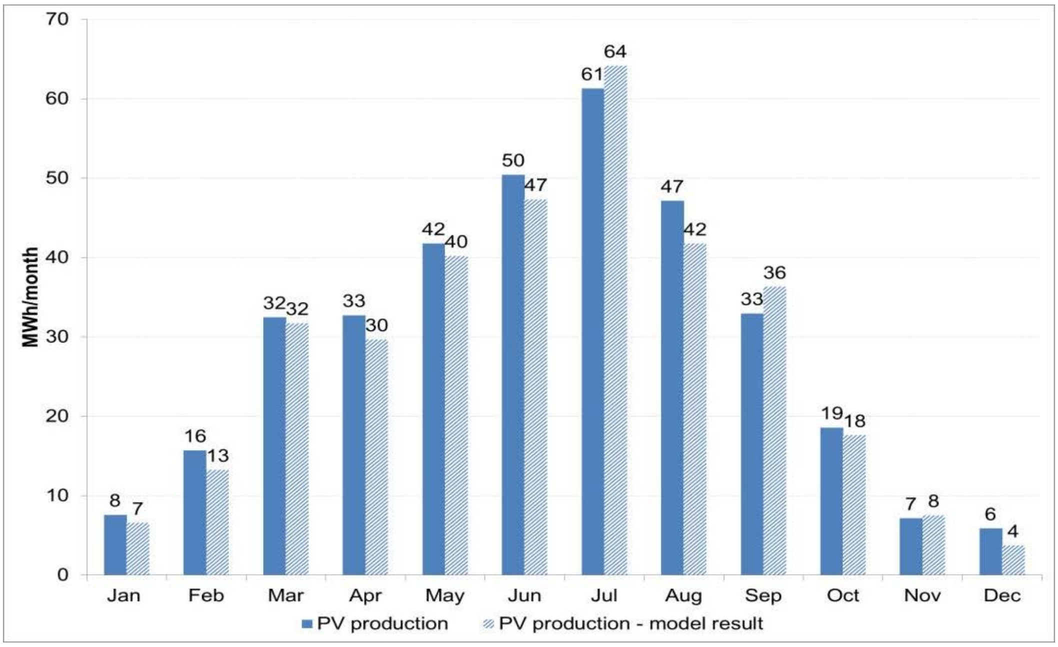

*Figure 5. Comparison of measured monthly PV production of BF2 + BF5 with model results**

*Only annual measurements for BF5 PV production are available, the monthly breakdown is estimated according to BF2 monthly profiles.

3.2 Comparison of electricity demand of network pumps

In figure 6 a monthly comparison of measured electricity consumption of network pumps with modelled results is shown. The model was calibrated such that the electricity consumption for winter months matched measured values. Despite this calibration, there is a large difference between modelled results and measured values. The total electricity demand of network pumps as calculated by the model is 26 MWh/year while the measured value is 53 MWh/year. This difference is due to optimisation which minimises energy exchange in the network such that during summer there are fewer exchanges between buildings and the boreholes. Rather than sending heat energy recovered from freecooling to recharge the borehole, this heat is stored within the buildings and used to preheat domestic hot water. This is confirmed by analysing the results for heat exchanges between building nodes during spring and summer months. During these months, local exchanges between the buildings dominate and there is often no flow along several sections of the network. This differs from the real network operation where the network flow has not been optimised and all sections of the network are operated continuously throughout the year.

One of the objectives of this paper is to understand if there is potential for improvement in network operation. While optimisation results for pumping electricity are not conclusive, they do indicate that there is potential for improvement. A more detailed simulation model will be implemented in the future to point out if the low temperature network can be operated according to the energy exchanges calculated by the model.

Besides this, the measurements for electricity demand for pumping were found to be highest during spring 2014, when the borehole field was completely discharged and its temperature dropped down significantly. This could be another reason for higher than expected pumping electricity demand, since the smaller temperature difference between the inlet and outlet of the borehole field results in the increase of the mass flow. A comparison with measured values when the borehole is operated in a more stable/sustainable situation might also result in a better match between measured values and model results.

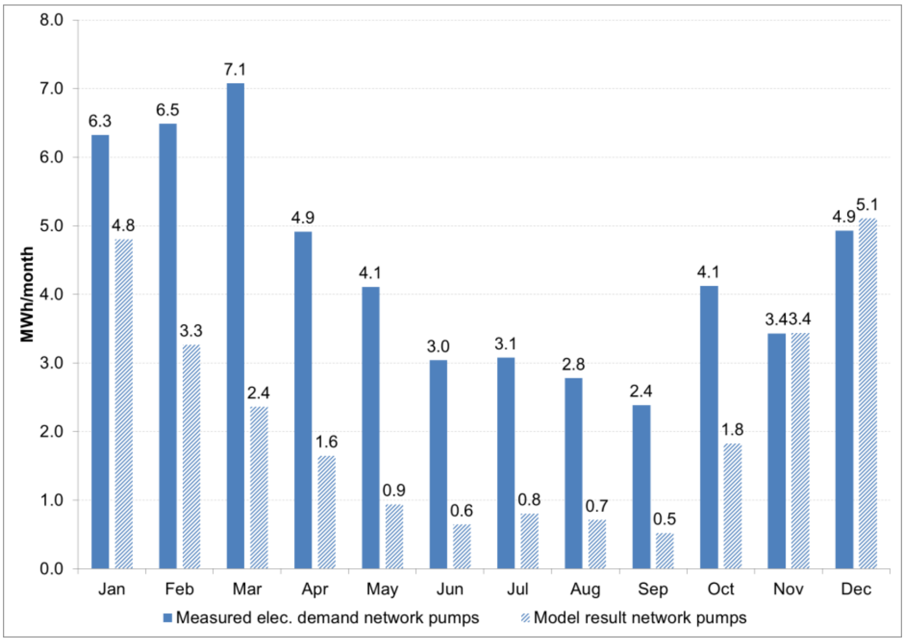

Figure 6. Comparison of measured electricity consumption of network pumps with model results

3.3 Comparison of electricity demand and heat intake of heat pumps

In figure 7a, 7b, and 7c, the electricity consumption of the heat pumps (HPs) and the heat intake of the low temperature heat pump are compared to model results. During certain months the HPs in BF2 and BF5 were shut down and substituted by electric heating to prevent undercooling of the borehole field. This change in operation could have impacted the coefficient of performance (COP) of the heat pumps during these months. Additionally, this results in lower heat intake and electricity consumption of the heat pumps. Since the optimisation model uses a fixed yearly COP value and the total heating and hot water demands are supplied only by heat pumps (no electric heating is considered unlike in reality), differences are observed between measured values and model results. The results are assumed to be verified, keeping in mind the differences in COP and system operation.

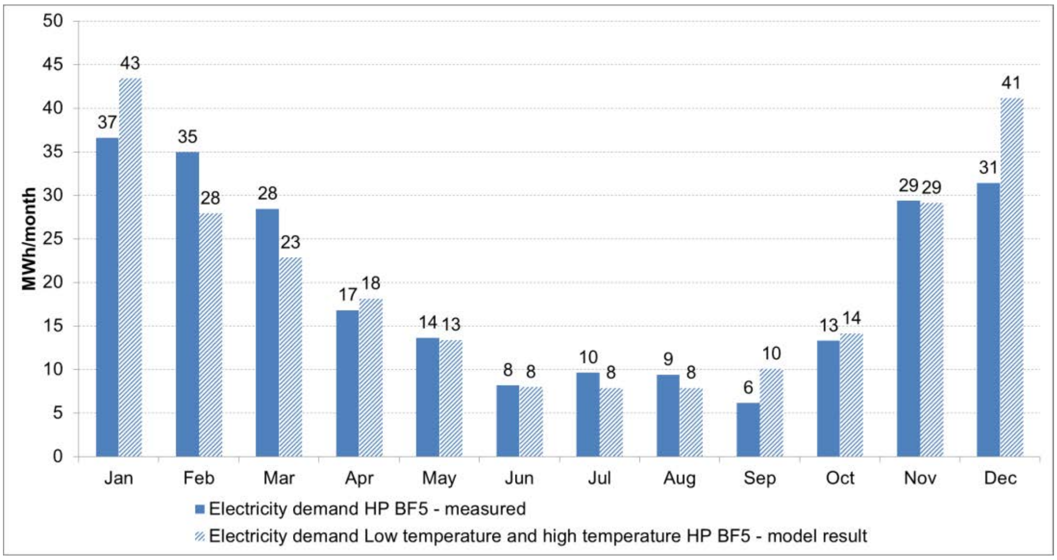

Figure 7a. Comparison of measured electricity consumption of the low and high temperature heat pumps in BF5 with model results

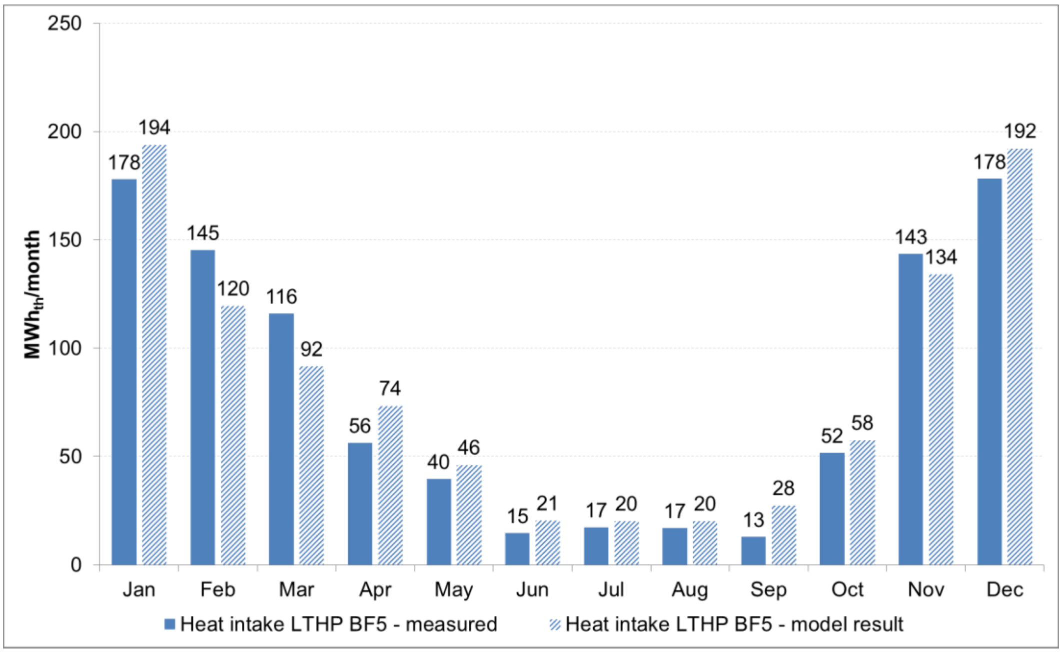

Figure 7b. Comparison of measured heat intake of the low temperature heat pump in BF5 with model results

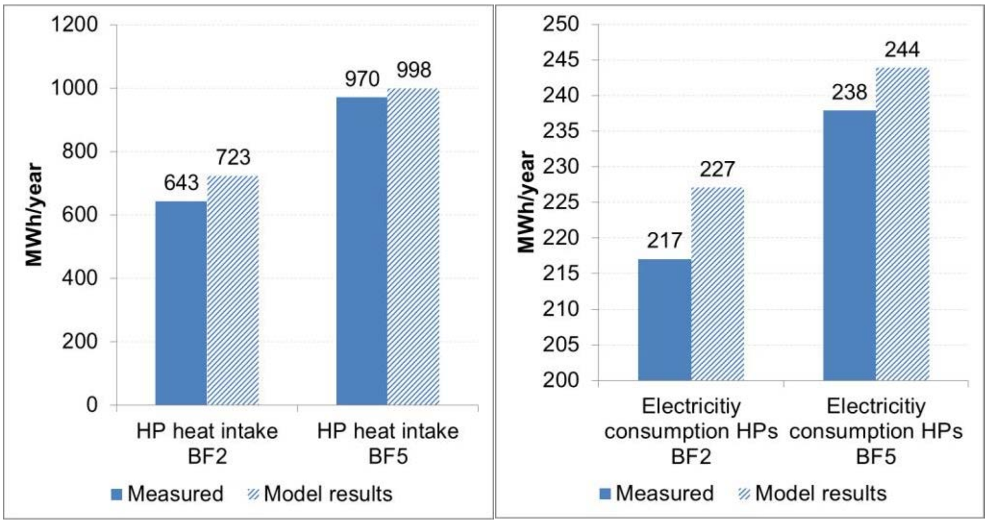

Figure 7c. Comparison of measured electricity consumption and heat intake of heat pumps in BF2 and BF5 with model results

3.4 Comparison of network heat deficit

In the monitoring report the heat deficit in the network was calculated as the difference between the heat intake of the heat pumps in each building and the heat input from the buildings into the network (from freecooling). These values were compared with modelled results for heat intake into building nodes and heat output into the network at building nodes. The total network deficit calculated by the model is in agreement with the measured value (figure 8), however there is a clear difference in the amount of heat sent into the network and drawn from the network between measured and modelled values. This again explains the lower electricity requirement for pumping calculated by the model, as discussed in the previous paragraph.

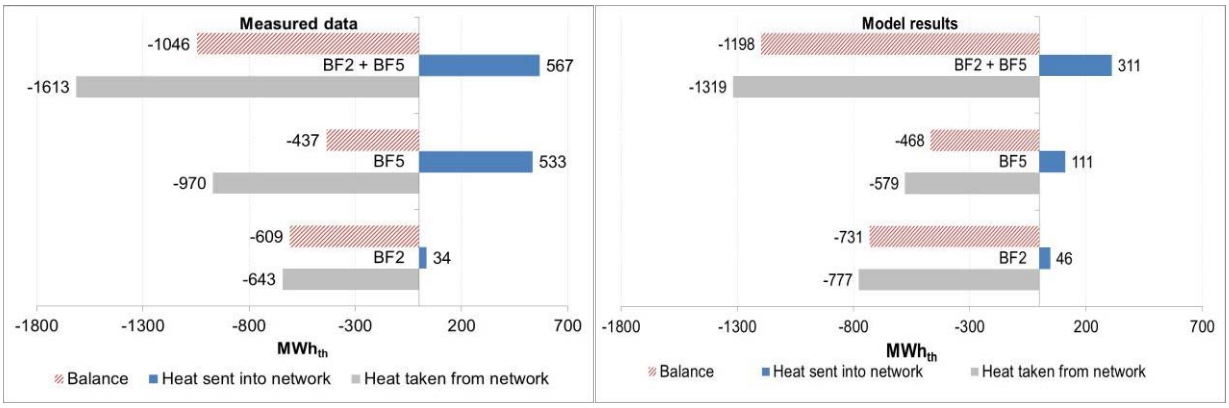

Figure 8. Comparison of measured heat balance for BF2 and BF5 with model results

3.5 Comparison of on-site electricity production and consumption

The total electricity demand to provide heating and hot water is compared with the electricity produced by the solar panels in figure 9a (measured values) and 9b (model results). The total measured electricity demand is the sum of electricity demand of heat pumps, network pumps and additional electric heating. The total electricity calculated from the model is the sum of electricity consumption of heat pumps and network pumps. In figure 9c, the modelled results for the amount of electricity injected into the grid are indicated in the graph. There is no monitoring of the electricity injected into the grid, but the model provides indicative values of it. These values can help for the future design and operation of the site, especially to increase self-sufficiency. The results indicate that there is a mismatch between demand and production of electricity – most of the PV production occurs during summer months while the electricity demand for heat pumps is higher during winter months. Thus it is clear that the site would benefit from seasonal storage capacity of the electricity produced on site. One option would be to convert this electricity to heat – this will be further explored in the base case model where BF2, BF5 and BF3 are modelled along with an air source heat pump (ASHP) which recharges the borehole field during summer months. Another storage option to be considered is the installation of battery storage (section 4.1).

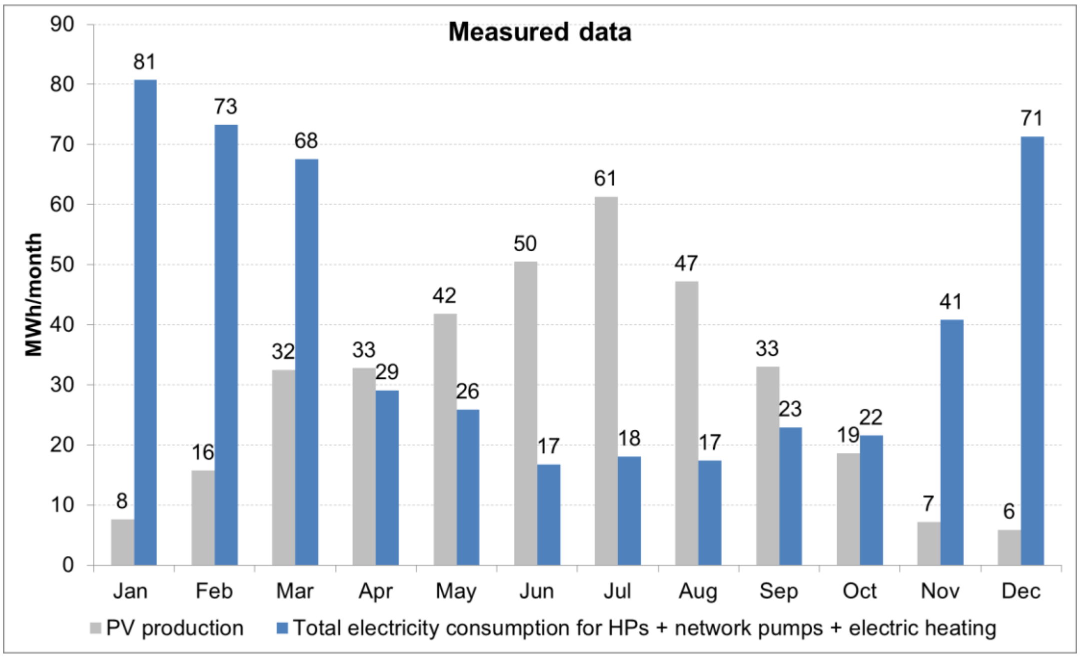

Figure 9a. Comparison of measured total electricity consumption with measured production for BF2 + BF5

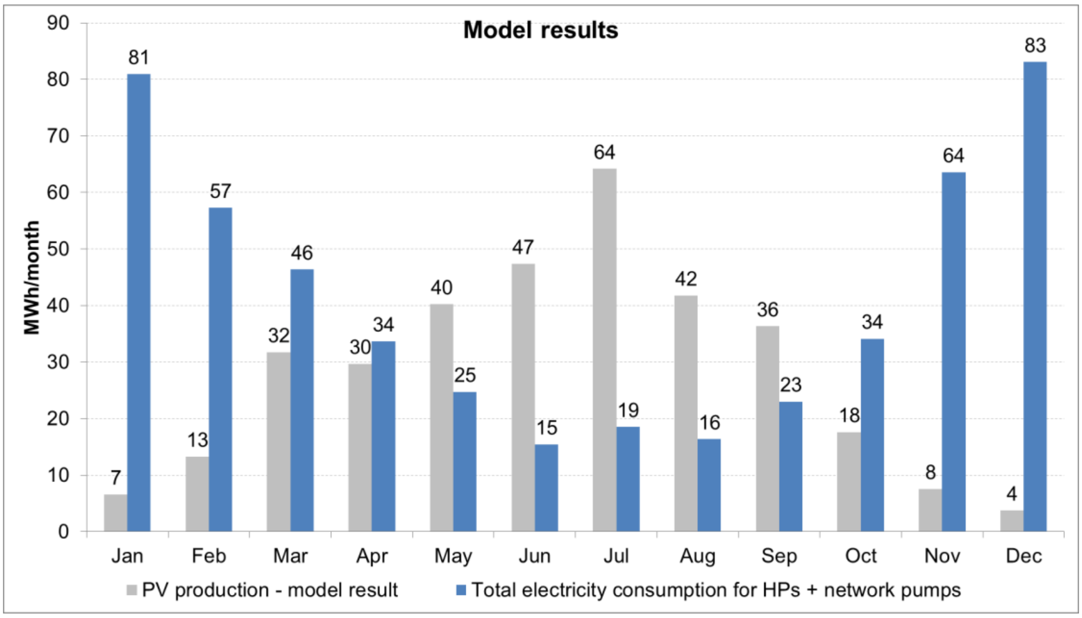

Figure 9b. Comparison of model results of total electricity consumption with model results of production for BF2 + BF5

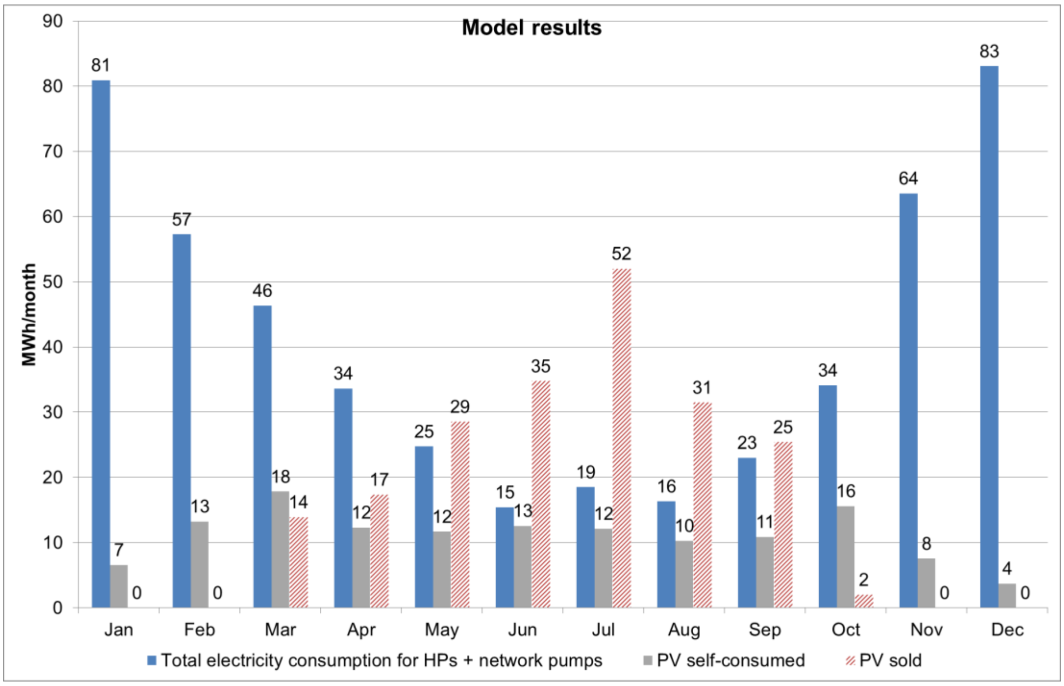

Figure 9c. Comparison of model results of total electricity consumption with self-consumed production and feed-in into the grid for BF2 + BF5

3.6 Base case with BF2, BF5 and BF3

Following the verification of the initial model, buildings of building site 3 (BF3) were included in the optimisation model. BF3 consists of nine residential buildings whose demand profiles are assumed to be similar to the residential buildings in BF2. The results of BF3 could not be validated completely as monitoring data for this site is currently not available (except for the electricity production of the PVT). However, the model results were compared with calculations of expected demand (figure 10). The comparison of model results of total heat demand of BF2, BF5 and BF3 to model results of PVT thermal production is shown in figure 11. While these results do not consider fluid temperatures, they indicate that during spring and autumn the thermal production of PVT panels is sufficient to meet thermal demand of the buildings in BF2, BF5 and BF3.

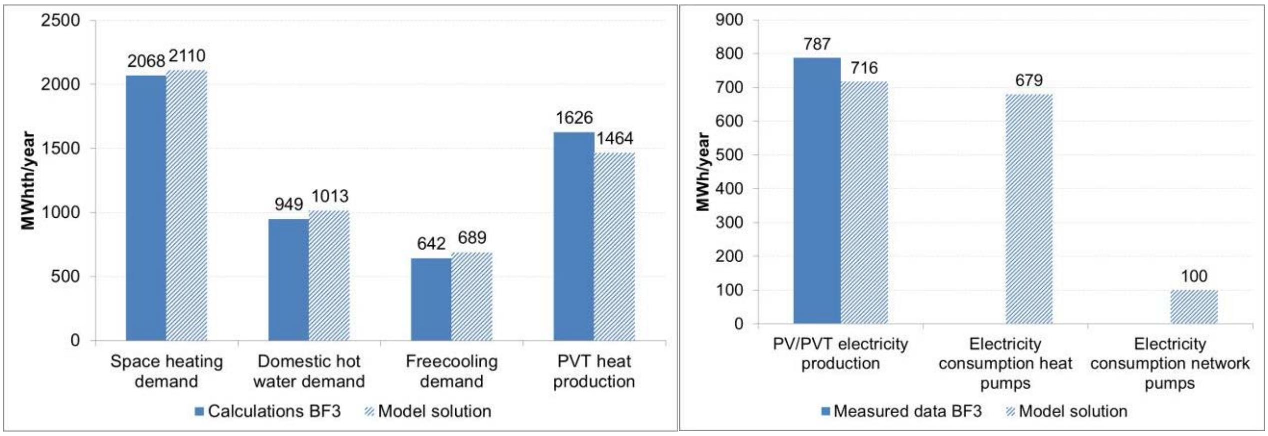

Figure 10. Comparison of model results for BF2 + BF5 + BF3 with calculations (left) and measured data (right).

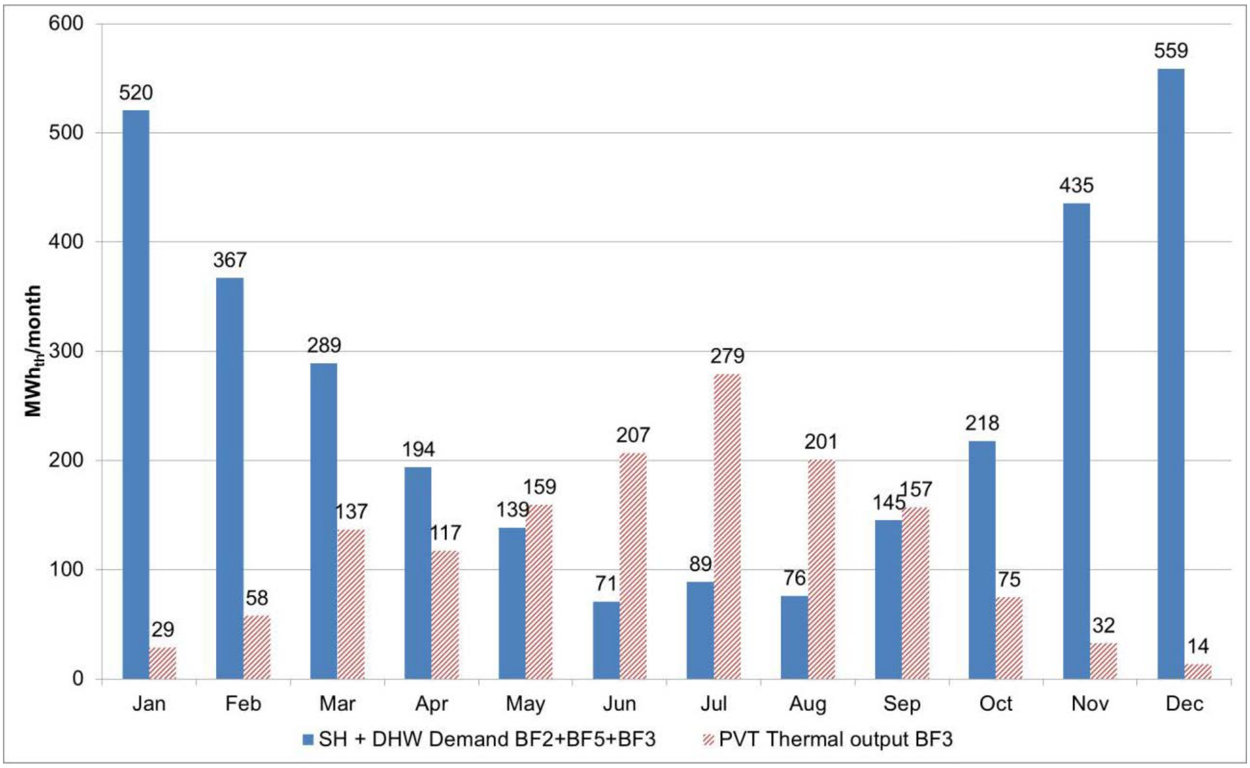

Figure 11. Comparison of model input for BF2 + BF5 + BF3 thermal demand (SH+DHW) with model results of thermal output of PVT panels in BF3

4. Scenarios

4.1 Scenario: BF2 + BF5 + BF3 + additional battery + additional PV

Within the optimisation framework, scenarios for complementary technologies were modelled. Due to high dependency on electricity produced on site, one of the scenarios selected was the installation of additional PV or additional batteries on site. The simultaneous optimisation of both costs and emissions was used to obtain a Pareto front in figures 12 a, 12 b and 12 c. When only additional batteries are installed, optimisation results show that once a certain capacity of battery has been reached; in this case 40 kWh; further increase in installed battery capacity does not significantly decrease electricity imported from the grid. This is because the battery provides storage for the daily timescale; while the effective time shift in demand and production on site is in the range of months. Thus batteries can reduce electricity import by approximately 20%, while the further decrease of electricity import would require additional production or long-term storage equipment. The optimal amount of additional PV panels would be 2776 m^2 and for the case where both batteries and PV is installed the optimal equipment would be 1015 m^2 PV and 40 kWh batteries. It was assumed that the maximal (hourly) value of PV power is an adequate design value to illustrate the effects of battery capacity on the self-sufficiency (in this case 40 kWh). If instantaneous time steps (instead of hourly values) were considered, the gap between PV production and electricity consumption would be higher and this would result in a higher required storage capacity.

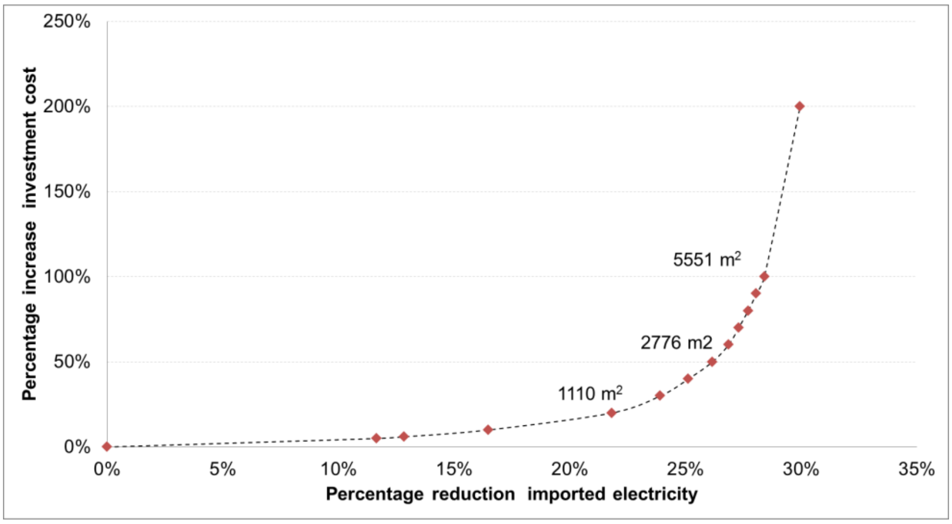

Figure 12a. Pareto front of optimal amount of additional PV area

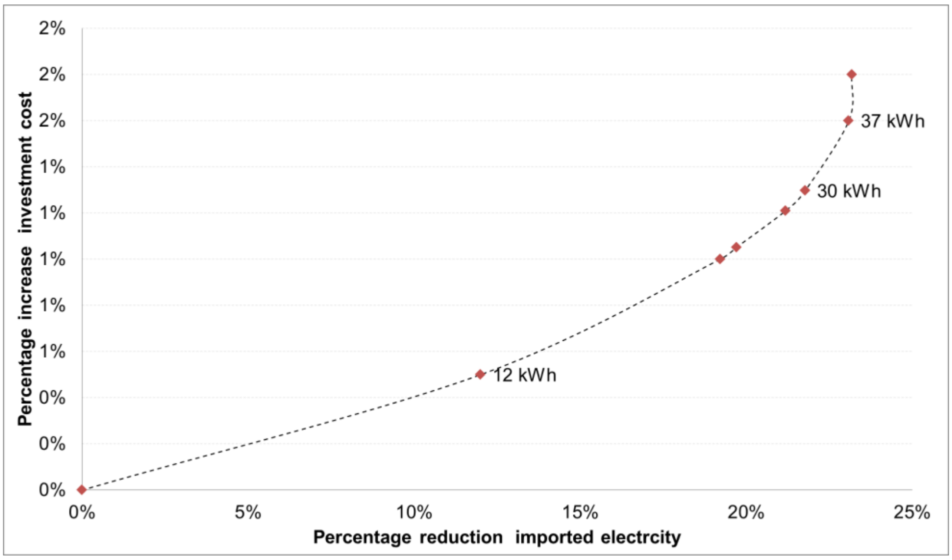

Figure 12b. Pareto front of optimal battery capacity

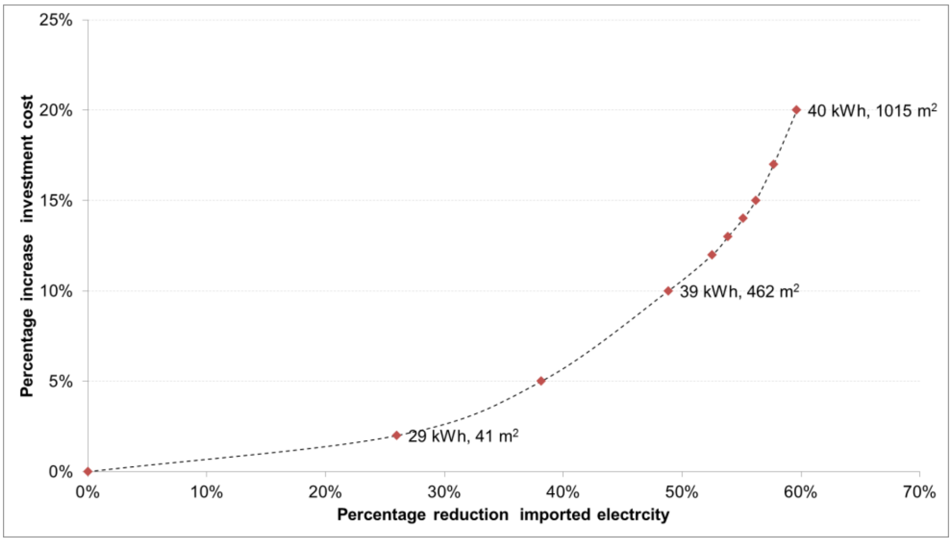

Figure 12c. Pareto front of optimal battery capacity and PV area

4.2 Scenarios: replacement of PV panels in BF2 and BF5 with PVT

An additional scenario which was modelled is the replacement of PV panels on BF2 and BF5 with PVT panels. The analysis was carried out assuming that PV panels on BF2 and BF5 would be replaced by PVT, while buildings in BF3 would continue to have existing PVT panels.

The results of this optimisation indicate that additional PVT panels (2651 m²) can decrease electricity import by approximately 5% and eliminate network heat deficit. The model results for heat intake from the heat pumps is 1601 MWh while the amount of heat injected into the thermal network is 2445 MWh. This results in a positive heat balance, with 844 MWh of heat excess which is stored in the borehole field. It is important to note that these results are theoretical values which do not take into account any constraint on the maximum allowable temperature of the network, in order to guarantee free-cooling operation.

5. Discussion and future outlook

This research work shows that it is possible to calibrate and verify an optimisation model with monitoring data. The modelled results obtained here are reasonably close to measured data. Furthermore, modelled results are able to provide additional information about the system, for example the amount of electricity injected into the grid or the electricity demand for heat pumps and network pumps which are not monitored in BF3. Differences between monitoring data and model results also help to identify important constraints in the real network, which are sometimes overlooked.

As highlighted in the monitoring report [1], one of the main challenges of the Suurstoffi site is the sustainable operation of the borehole field which supplies the LTN. The model results indicate that there is a potential to reduce network deficit and regenerate the borehole field (with additional PVT panels) if a solution is found to overcome network temperature constraints. Optimum values for battery capacity and additional PV area which would help to increase self-sufficiency are also presented. Optimisation results also indicate a potential to reduce the electricity demand of network pumps through the implementation of a control strategy or adaption of the hydraulic design for network flow. It is planned to study this further by developing a simulation model which considers mass balances, pressure drops and network temperatures as well as energy balance. The first detailed models for LTN are developed [8]. Future measurements of mass flow and pressure drop along network pipes would thus be essential to better model and understand system operation.

While the model results are only indications and do not take into account all system constraints faced in reality, they can nevertheless be used to identify specific elements of the system which need to be studied in more detail. The results presented in this paper provide insights on the extent into which the system design can be improved, and point out the benefits and drawbacks of the various options. Future modelling and simulation of the thermal network would be the next step towards improving the design and operation of the Suurstoffi network.

In conclusion, modelling and monitoring have proved their utility for the sustainable design and operation of buildings and districts, while conventional planning methods fail to point out flexible long term solutions. Referring to low-energy districts modelling and monitoring gain additional relevance as valuable tools in the planning process as there are no existing optimisation methods yet to maximise energy self-sufficiency, or to provide system services for the electrical grid. The need for such tools is emphasised through the considerable impact of the calculation accuracy on the sustainable functioning of low-energy districts.

6. References

[1] Vetterli N., Settembrini G., Nachhaltigkeitsreporting Zug Estates Jahresbericht 2016 (inkl. Prognose 2017 - 2021), 2016

[2] Vetterli N., Brücker S., Monitoring Suurstoffi – Monitoring einer thermischen Arealvernetzung in Kombination mit einem Erdsondenfeld, Jahresbericht 2014, Bundesamt für Energie BFE, Bern, 2015

[3] Sulzer M., Vetterli N., Dynamic analysis of the low-temperature district network ‘Suurstoffi’ through monitoring. CISBAT, International Conference Future Buildings & Districts, EPFL, Lausanne, 2015

[4] Kräuchi P., Sulzer M., Schluck T., Non-linear thermal networks – how can a meshed network improve energy efficiency, CISBAT, International Conference Future Buildings & Districts, EPFL, Lausanne, 2015.

[5] Orehounig K., Evins R., Dorer V., Integration of decentralized energy systems in neighbourhoods using the energy hub approach, Applied Energy 154, 277–289, 2015

[6] Evins R., Orehounig K., Dorer V., Carmeliet J., New formulations of the ‘energy hub’ model to address operational constraints, Energy 73, 387–398, 2014

[7] Morvaj B., Evins R., Carmeliet J., Optimising urban energy systems: simultaneous system sizing, operation and district heating network layout, submitted to Energy, 2016

[8] Kräuchi P., Schluck T., Sulzer M., Modelling of low temperature heating networks with IDA-ICE, publication accepted for BauSIM 2016, Dresden Germany.