Energy Inclusive Housing Solution Using a Hybrid District Heating System

PART I

Microgrid design with residential photovoltaic to power the district heating system to provide heat and electricity for Meerstad, the Netherlands.

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Alex Mazzon, UAS Hanzehogeschool

***Abstract*—This research is an analysis of the technical, economic, social and legal aspects of the establishment of a local district heating (DH) cooperative in a new residential area in Meerstad, a neighbourhood of Groningen, the Netherlands.**
The presented design is a hybrid district heating system that uses DH stations and a microgrid powered predominantly by residential photovoltaic (PV). The DH units are Eco Genie stations by Shell that were already implemented before in a pilot-project in Paddepoel-Noord, another neighbourhood of Groningen. This DH units basically consist of heat pumps and large scale boilers. The objective was to estimate the surplus electricity that can be produced from residential houses in order to power the heat pumps. For this purpose, a microgrid was designed with a static model.
Different scenarios are presented, where the efficiency of the heat pumps and the photovoltaic design varies. In the best case, with high efficiency heat pumps and PV panels, a surplus of 13,816 MWh per year was calculated that covers 69 percent of the heat pump's consumption. In the worst case, with low efficiency heat pumps and PV panels, a coverage of 49 percent was calculated. Thus the results indicate that it is technically feasible to implement the proposed solution.

***Index Terms*—microgrids, residential photovoltaic, district heating, energy cooperatives**

I. Introduction

GLOBALLY, urban areas are expanding at a faster rate than their populations and urban densities of cities have been declining (United Nations, 2020). The United Nations (UN) argue that this trend creates serious repercussions for environmental sustainability at the local, regional and global scale. Thus the UN indicates in the Sustainable Development Goal 11 that "better management of urban growth will be crucial in order to guarantee sustainable urbanization" (United Nations, 2020).

According to Nabielek, Kronberger-Nabielek, and Hamers (2013), the Groningen urban region has a monocentric structure and "Urban expansions between 1989 and 2008 were relatively modest (in comparison with the Amsterdam and Rotterdam-The Hague regions) and they are mainly concentrated around the city of Groningen and some surrounding small towns". This new urban development is located adjacent to existing settlements and new urbanisation shows a very compact structure (Nabielek et al., 2013). One of these new neighbourhoods of Groningen is Meerstad, where a new residential area of around 6500 new houses (see Fig. 1 and 2) is expected to be built (Meerstad, 2020) in the next twenty years. To promote a sustainable development of this area, the energy cooperative "Meerkracht" was founded (Meerkracht, 2020) that primarily aims to provide energy inclusive housing solutions. The main activity of the cooperative is the promotion of low-carbon energy solutions in order to supply the houses with sustainable electricity and heat. A member of the energy cooperative, Mr. Gerard Martinus [1] , is the case owner of the present research.

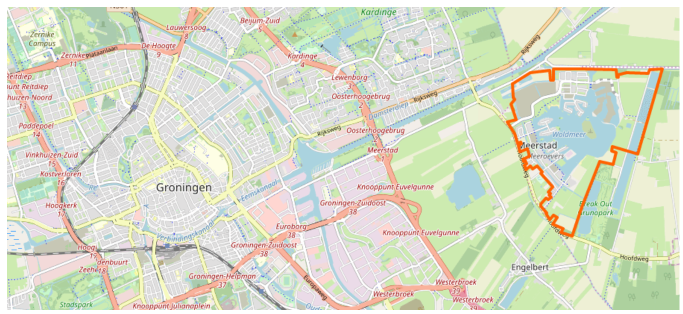

Fig. 1. The neighbourhood of Meerstad, a new residential area located at the east of Groningen (Source: OpenStreetMap, 2020).

This report is part of a research carried out with a group of four students [2]. The group research shows one approach of how the houses in Meerstad could be supplied with heat and electricity using a hybrid district heating (DH) system. This hybrid DH system provides the heat to the houses. It runs on heat pumps that are powered by electricity produced locally through photovoltaic (PV) installations and other local power plants. The PV panels are installed on the rooftops of the houses and the electricity is transported within the area with a microgrid. The present paper presents the first part of the group research, in which the microgrid for the hybrid DH system was designed with a simplified model. The DH system and the microgrid are explained more in detail in the next two sections (I-B and I-C).

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[1]Mr. Gerard Martinus, Energy Cooperative Meerkracht, info@meerkracht.org

[2]Group composed by the members: Alex Mazzon (author of this paper), Viktor Makkas, Alex Puff and Odhran Crolly

TABLE I
ALL SUB-RESEARCH QUESTIONS AND THEIR ASSOCIATED ACTIVITIES.

	Research Question	Activities
1	RQ1: How much surplus solar electricity can be produced in Meerstad from residential PV installations?	A1: Estimation of the amount of surplus solar electricity that can be produced from residential photovoltaic installations.
2	RQ2: What merits does the proposed system have compared to a district heating solution supplied by conventional energy?	A2: Investigation of the merits of the proposed system compared to a district heating solution.
3	RQ3: What housing design suit the limits of the proposed system?	A3: Assessment of the physical restrictions of housing construction.
4	RQ4: What are the total investment costs of this system and the payback period?	A4: Estimation of the total investment costs and the Net Present Value of the project.
5	RQ5: What are the resulting infrastructural challenges?	A5: Investigation of the infrastructural challenges.

A. Research Questions & Objectives

Basically, the hybrid DH system is composed of the Eco Genie Stations that provide heat and the microgrid that interconnects electrically the households. The PV installations provide electricity to the houses for their own consumption and for the heat pumps of the Eco Genie stations that in turn supply them with heat through the DH system.

The overall objective is to assess the feasibility of such a hybrid DH system for the Meerkracht energy cooperative. Thus in a first research phase the group identified the following research question: Is a hybrid DH system, supplied by heat pumps powered by a microgrid in combination with large scale boilers, a feasible solution for Meerstad? The group further defined that the purpose is reached by providing answers to the sub-questions defined in table I. Respectively to the sub-questions, the specific activities were defined. This information will facilitate the planning, modelling and implementation of future energy installations by the Meerkracht energy cooperative.

The first sub-question and respectively activity A1 was carried out by the author of the present paper (see chapter II Methodology). Therefore, the primary objective of the present research was to estimate the amount of surplus solar electricity that can be produced from the residential photovoltaic installations. For the other sub-questions the reader may refer to the reports of the other group members.

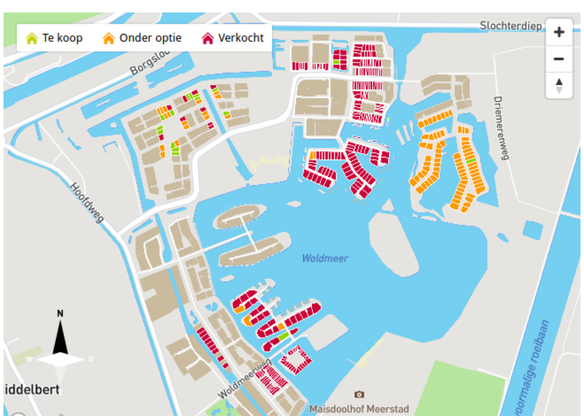

Fig. 2. New housing project in Meerstad. Sold houses in red and orange, for sale in green, potential areas for new houses in brown (Source: Meerstad, 2020)

B. Providing Heat for Meerstad with a District Heating System

On a global scale, according to IRENA (2017), ”a switch to renewable energy sources for centralised heating and cooling can help meet rising urban energy needs, improve efficiency, reduce emissions and provide cost-effective temperature control”. On a local scale, the environmental goal of the municipality of Groningen is to reduce 50% of its CO2 emissions by 2025 and to become carbon-neutral by 2035 (Gemeente Groningen, 2011, 2015). Furthermore, Groningen wants to be natural-gas-free by 2035 (Gemeente Groningen, 2016), due to the earthquakes caused by the extraction of gas from the Groningen gas field lying underneath the region.

Today there are three sustainable heat sources to replace natural gas: District Heating (DH) systems, all-electric systems and hybrid systems (green gas combined with hydrogen) (Knol, 2018). The research group decided that DH systems could be a suitable solution for Meerstad for three reasons. First, it allows integration into urban environments due to the reduced space needs (IRENA, 2017). Second, the Dutch-British oil and gas multinational Shell supports a cooperative start-up that aims to design, build, own and operate a pilot DH system called Eco Genie 2.0 (Shell, 2020) in Paddepoel-Noord, another neighbourhood of Groningen and this project inspired the present research. Knol (2018) wrote a master thesis about the Eco Genie 2.0 in collaboration with Peter Breithaupt, the coordinator of the research at Shell. The third reason is that, given the situation of Meerstad, the group estimated that it is more efficient to transform locally produced electricity into heat and store it in large-scale water boilers rather then transforming it to hydrogen or other types of storage potentially suitable for Meerstad.

Moreover, Averfalk, Ingvarsson, Persson, Gong, and Werner (2017) argues that ”Power-to-heat installations in district heating systems are favourable as they provide flexibility in the electricity system, since they can be operated when electricity prices are low and shut down when prices are high”. Furthermore, power-to-heat installations are ”competitive because of low specific investment and installation costs for large electric boilers, heat pumps, and heat storages”

(Averfalk et al., 2017).

The Eco Genie 2.0 is seen as a DH unit that comprehends heat pumps and three large scale boilers as storage. Therefore, the unit needs exclusively electricity for the heat pumps in order to provide heat to the surrounding houses. The powering of this heat pumps through the microgrid is described in the following section I-C.

C. Powering of the Households and the District Heating System with Solar Electricity and a Microgrid

In order to make the powering of the heat pumps of the Eco Genie 2.0 sustainable, the group decided to supply them as much as possible with locally produced renewable energy sources. One way of doing so is a microgrid that supplies the heat pumps. According to Schiffer et al. (2016), "microgrids have been identified as key components of modern electrical systems to facilitate the integration of renewable distributed generation units". Moreover, microgrids have evolved to become an economically viable alternative to challenging investments that make the transmission network compatible with the emerging decentralized electricity production (Mahmoud, Azher Hussain, & Abido, 2014).
The chosen design for the generation within the microgrid is predominately residential solar electricity generated by all houses through PV installations. As a backup the heat pumps are powered by the existing electricity grid or other local power plants that should run preferably on renewable energy sources (e.g. wind or biogas) as well. First, the electricity produced by the PV panels of all households is consumed by all households that are interconnected through the microgrid. The primary aim of the interconnection is to achieve a higher self-consumption of the solar electricity compared to a single house installation, because the load is more constant throughout the day. Second, all the surplus electricity is consumed by the heat pumps of the DH system.

According to Zambroni de Souza and Castilla (2019) "Microgrids can be understood as a complete electrical power system in all characteristics which are inherent to them but on a tiny scale". In the case of the present research the microgrid is thought to operate independently and with a connection to the distribution system. Such microgrids provide a higher reliability than that of the distribution grid, because loads can be served even if the transmission network is down due to a fault (Mahmoud et al., 2014). Furthermore, they give control over the produced and consumed energy within the microgrid (Zambroni de Souza & Castilla, 2019). According to IEEE (2002), microgrids are networks composed of loads, storage systems and distributed generation units in a local distribution network. In the case of the present research these are respectively the new 6500 households and the heat pumps (loads), the large-scale water boilers (storage), the PV installations (distributed generation units) and the distribution network in the area of Meerstad.

II. Methodology

In order to answer the main research question, the following conceptual approach was designed (see Fig. 3) by the research group. This methodology allowed the team to split up the interlinked research based on the four main fields of investigation: technical, economical, social and legal. The research was carried out in three phases. Phase 1 and Phase 3 were carried out by the whole research team. In Phase 2 the activities defined in table I were assigned individually as follows: A1 to Alex Mazzon, A2 to Alex Puff, A3 to Viktor Makkas and A4 to Odhran Crolly. Activity A5 was part of phase 3 and therefore carried out by the whole group. Moreover, during the course of the research, in the period between September 2019 and January 2020, monthly meetings have been held with the case owner and Professor Kuiken in order to get feedback on the progress of the work.
In the first phase, the problem statement and the research question were defined. This lead into phase two, during which the team members separately investigated their sub-question. During the third phase, the group gathered all individual outcomes in order to answer the fifth research question and the overall research question. Conclusively, the group wrote a list of recommendations for the energy community of Meerkracht. The three phases are explained more in detail in the following sections II-A, II-B and II-C.

A. Phase 1: Problem Statement, Literature Review and Research Question

The main problem that is faced, is to find a most cost-effective but also sustainable solution for the Meerkracht energy cooperative. The problem statement was identified through preliminary literature review and in collaboration with the case owner and Professor Kuiken. The literature review was carried out as desk research. The most important papers

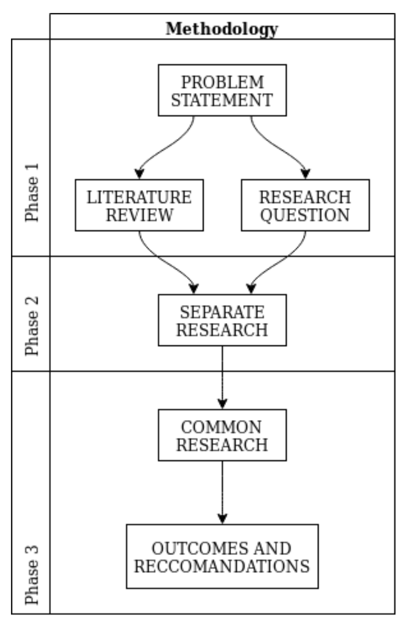

Fig. 3. Methodology: The three phases of the research (Own representation).

identified are: the publication about the Eco-Genie pilot project in Paddepoel-Noord from the energy cooperatives ”Paddepoel Energiek” and ”Grunneger Power” just available in Dutch (Breithaupt, Walstra, & Broekhuis, 2019) and the master thesis about local power-to-heat DH cooperatives and the Eco Genie 2.0 (Knol, 2018). Furthermore, the preliminary literature review showed that the exact planning of a micro-grid is an extensive task. Thus, due to time limitations of this research, assumptions were needed that constitute a high risk of unsure and therefore weak outcomes.

During the phase 1 a project proposal was written and presented to the case owner. The expected outcome stated in the project proposal is to give an answer to the main research question, based on the technical, economic, social legal analysis that will be conducted with the proposed methodology. The result could be positive or negative, but feasible or not, the project outcome will be considered successful even if it turns out that the project is not worth pursuing.

After an agreement on the project proposal, the project plan was defined. This plan defined the organization for the second and third phase, by assigning the activities of table I to the individual group members. Furthermore, a Gantt chart was created for time management and collaboration.

In order to ensure the best possible quality of this work for the Meerkracht energy cooperative, each group member focused mainly on a sub-question that is more oriented to his own discipline and background.

B. Phase 2: Separate Research

This phase allowed to split up and carry out individual research based on exploiting out background skills. Communication and co-ordination were vital in this phase as the individual research aspects are also interlinked. The first sub-question and respectively activity A1 is carried out by the author of this paper. For the other sub-questions the reader can refer to the reports of the other group members.

The aim of activity A1 is to estimate the amount of surplus solar electricity that can be produced from the residential photovoltaic installations. In order to calculate this value a simplified model was created and explained with all assumptions in chapter III Microgrid Model for Meerstad. The model is based on consumption and production numbers retrieved from various sources. All numbers related to energy are taken per year (in kWh/a).

The methodology used is scientific modelling. The framework defined by Bryden (2008) was used to create a model based on basic calculations with static numbers. This framework is illustrated in figure 4. According to Bryden (2008), ”the main focus of the framework is on scientific modelling and the interface between a conceptual model and a working model”. Bryden (2008) defines that ”whereas conceptual model may remain vague in places, a working model produces results which are used to refine and update the conceptual model”. The microgrid model was simplified in accordance with the case owner in order to estimate its design and to get an idea of its benefit.

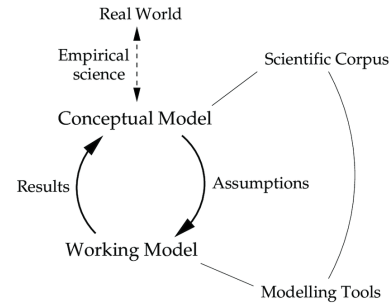

Fig. 4. Scientific modelling method used for the modelling of the microgrid. Source: Bryden (2008)

C. Phase 3: Common Research, Outcomes and Recommendations

After concluding the second phase, the group gathered the outcomes. Activity A5 was completed together using the outcomes in order to identify a list of infrastructural installations that are needed. From these installations a list of infrastructural challenges was identified by desk research.

After all activities were completed, the group gave an answer to the main research question based on all previous activities. The result is a advice formulated in one written page for the Meerkracht energy cooperative based on the information gained through the group research. The method was to discuss each sub-question in depth and all aspects of the results were critically scrutinized and potentially improved, in order to formulate the best approach to answer the main research question.

III. Microgrid Model for Meerstad

A basic model of a microgrid was created with Excel in order to calculate the amount of surplus solar electricity that can be produced from the residential photovoltaic installations. The following chapters present the model design, all assumptions taken and the optimization process as well as the different scenarios.

A. Model design

A microgrid is an integration of various units, that consists basically of distributed generation (DG) units, energy-storage

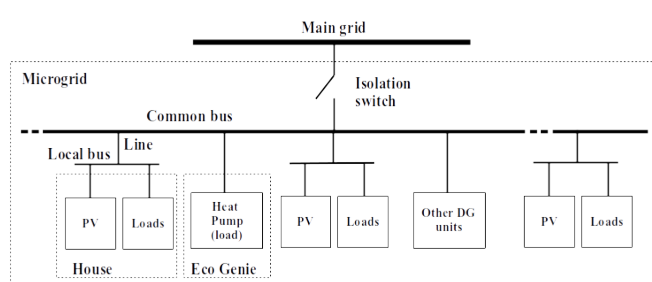

Fig. 5. Microgrid model for Meerstad that interconnects 6500 houses, 13 Eco Genie Stations and other distributed generation (DG) units. Adapted from Pogaku et al. (2007).

units, controller units and conventional loads. Therefore, the modelling of a microgrid varies with its configuration and components used (Mahmoud et al., 2014). Various modelling approaches can be found in Dobakhshari, Azizi, and Ranjbar (2011) and extensive literature exists about modelling and controlling of microgrids. Figure 5 presents the model of the microgrid used for the present research, adapted from Pogaku et al. (2007). It consits of 13 DH stations (Eco Genie) that include the heat pumps, 6500 houses each with its loads and PV installations and other distributed generation units.

The model is based on consumption and production numbers retrieved from various sources. All numbers related to energy are taken per year (in kWh/a). Therefore, the model is a static model of a microgrid that connects the PV production of 6500 households to their own consumption and to thirteen DH stations.

The inputs of the models related to the households are: the amount of houses, the electricity and heat consumption per house and the PV production. The inputs for the DH system are: the amount of district heating units, the heat delivered by one unit, the COP and the respective heat pump consumption. From these inputs the microgrid electricity loads and generations are calculated.

The PV production per household and the COP of the heat pumps are the only two variables of the model that were varied in order to create different scenarios. The total PV production is calculated by multiplying the PV production of one house with the amount of houses (6500). It was assumed that 30 percent of the PV production can be consumed directly by the households (see section III-B). Therefore, from the total PV production per year, the direct consumption of all households is calculated simply by multiplying it with the 30 percent. The surplus for the heat pumps is then calculated with the remaining energy taking into account 5 percent of losses.

From the absolute values three relative values are calculated: Heat pump consumption covered by PV, houses consumption covered by PV and total electricity consumption covered by PV. Through this numbers the model can be optimized to a higher part of consumption covered by PV. Moreover, the energy that has to be provided from other sources within the microgrid or the existing distribution grid is the remaining amount that is not covered by PV.

B. Assumptions

Overall, the assumptions used for the calculations of the models are based on the Meerkracht case given by the case owner and on other different sources. The first assumption taken in accordance with the case owner is that 6500 houses will be actually built in Meerstad and that they will have an average household consumption for the region of Groningen. These consumptions are 2870 kWh/a of electricity and 13720 kWh/a of heat for a semi-detached house in the province of Groningen (StatLine, 2018).

In order to calculate the microgrid model in a static way, a central assumption was made: 30 percent of the total produced PV electricity production is consumed directly from the households. The surplus is used for the heat pumps of the DH units taking into account 5 percent of microgrid losses.

According to Breithaupt et al. (2019) one Eco Genie station delivers heat for 500 households. Therefore, the heat delivered by one Eco Genie station is assumed to be the multiplication of the heat consumption of one household times 500 households (6,860 MWh/a). From this heat amount delivered by one unit the heat pump consumption per unit is calculated with the COP (e.g. 1,960 MWh/a for a COP=3.5). The COP of the Eco Genie heat pumps was assumed to be 3.5 (standard efficiency) or 4.5 (high efficiency) in different scenarios, according to Breithaupt et al. (2019).

The PV production for one house was calculated with the Dutch PV portal v2.0 for PV system design by Veikko Schepel of the TU Delft (Schepel, 2020). For the PV calculations, two different types of panels were used, monocrystalline silicon high efficiency and monocrystalline silicon medium efficiency. It was assumed that 12 panels (about 24 square meters) will be installed per rooftop and that they will all have an orientation facing south (azimuth = 180 degrees). The module tilt is given by the rooftop angle of the houses given by the case owner and is assumed to be 60 degrees. Furthermore, the Dutch PV portal assumes 6.88 percent shading loss for rooftop PV systems due to surrounding objects.

C. Optimization and Scenarios

For the optimization of the microgrid, the COP and the PV design were varied in order to get different proportions of electricity covered by solar energy. With higher solar production the coverage by PV is expected to rise with constant COP. A higher COP means that the heat pumps consume less and therefore the solar coverage is also expected to rise with constant solar production.

The higher solar production can be achieved with more panels, with a better panel angel, with a higher nominal power or efficiency of the panel. The electricity consumption of the heat pumps can be limited by investing in better heat pumps with higher COP values. These variations affect the investment costs, which are not calculated in the model. The output that is considered is the amount of surplus electricity available for the heat pumps and the coverage by PV of the different loads (see Table II).

Four different scenarios were the efficiency of the heat pumps and PV installations is varied in order to present the functioning of the model and get different coverage proportions by PV. Moreover, also all the other values of the model can be changed, like the household consumption or the heat delivered by one Eco Genie station, but these were kept constant in order to create just four representative scenarios that demonstrate the functioning of the model.

For scenario 1 and 3 high efficiency monocrystalline panels were considered, whilst for scenario 2 and 4 medium efficiency monocrystalline panels were considered. In scenario 1 and 2 high efficiency heat pumps (COP=4.5) were considered, whilst in scenario 3 and 4 medium efficiency heat pumps (COP=3.5) were considered.

TABLE II
DIFFERENT SCENARIOS CALCULATED WITH THE MODEL

	PV production houses	**COP heat pumps**	**Total PV production**	**Total load heat pumps**	**Surplus for heat pumps**	**Micro grid Losses**	**Heat pump consumption covered by PV**	**Houses consumption covered by PV**	**Total consumption covered by PV**
	[kWh/a]	-	[Mwh/a]	[Mwh/a]	[Mwh/a]	[Mwh/a]	[%]	[%]	[%]
1	3,270	4.5	21,255	19,818	13,816	1,063	69%	34%	55%
2	2,980	4.5	19,370	19,818	12,591	969	63%	31%	50%
3	3,270	3.5	21,255	25,480	13,816	1,063	54%	34%	48%
4	2,980	3.5	19,370	25,480	12,591	969	49%	31%	43%

IV. RESULTS

The amount of surplus electricity generated from residential PV panels is dependent on the combination of technologies utilised. With the model created, four scenarios were created which result into different outputs for different combinations of high and medium efficiency PV panels as well as high and medium performance heat pumps (see first two columns of table II). With high efficiency PV panels and heat pumps a surplus of 13,816 MWh electricity per year was observed. This was the best-case scenario found that corresponds to a coverage of 69 percent of the total heat pump consumption by PV.

The same surplus as in scenario 1 is available in scenario 3, but the relative coverage of the heat pump's consumption by PV drops from 69 to 54 percent, because the COP changes from 4.5 to 3.5, meaning that the heat pumps consume more. In scenarios 2 and 4 the surplus drops to 12,591 MWh per year, because of less efficient panels. The corresponding relative coverage is 63 percent in scenario 2 and 49 percent in scenario 4.

Scenario 1 and 3 have a total PV production of 21,225 MWh/a (high efficiency panels) and scenarios 2 and 4 have a total PV production of 19,370 MWh/a (medium efficiency panels). The heat pump consumption amounts to 19,818 MWh/a in scenario 1 and 2 (COP=4.5) and to 25,480 MWh/a in scenario 3 and 4 (COP=3.5).

With the different combinations, the total electricity consumption covered by PV (last column) falls from 55 percent in scenario 1 to 43 percent in scenario 4. The house consumption covered by PV is always 30 percent of the total production (see section III-B Assumptions), respectively 34 percent (scenarios 1 and 3) and 31 percent (scenarios 2 and 4).

Moreover, the resulting microgrid losses amount to 1,063 MWh/a in scenarios 1 and 2 and to 969 MWh/a in scenarios 2 and 4.

V. DISCUSSION

The model of the microgrid and the results of the research can be used by the Meerkracht cooperative and indicate that it is technically feasible to implement the proposed solution. In this way the research contributes to the development of a carbon-neutral residential area in Meerstad. Nevertheless, the static model is an estimation of the microgrid and the assumptions taken could falsify the results. Therefore, a sensitivity analysis, verification and validation of the model is necessary in the first place. Furthermore, detailed planning and simulation is necessary for a more in-depth conclusion. For an actual implementation, more complex modelling and simulation is needed. The following software was researched and could be used in order to do so: MATLAB Simulink/Simscape (Matlab, 2020), PandaPower (Uni Kassel & Frauenhofer IEE, 2020) or HOMER (Homer Energy LLC, 2020).

VI. CONCLUSION

The merits of a microgrid system for Meerstad have been shown and how this system may contribute to the overall carbon-neutral aim of the Meerkracht cooperative. Technically, it is feasible to implement a microgrid system to power the heat pumps of the Eco Genie DH stations, because there is enough PV surplus electricity to partly power a good proportion of the heat pump's consumption. In the best case, 69 percent of the heat pump's consumption is covered by PV. At the same time, 34 percent of the household's electricity consumption and 55 percent of the total electricity consumption is covered by PV. Therefore, it can be estimated that more then half of Meerstad's heat consumption and more then a third of the residential electricity consumption can be covered with the proposed system.

The following is a list of recommendations that the Meerkracht cooperative may consider in the case of further research about about the microgrid:

- In order to achieve a high self-consumption of the locally produced electricity within the microgrid, as much households as possible should be involved, because this creates a more constant load throughout the day. The surplus should be consumed by the DH stations in order to produce heat for the houses.
- There should be always enough surplus electricity for the heat pumps. Therefore, industrial consumers could represent a problem due to their high electricity consumption. It should be considered to detach large-scale

consumers from the local microgrid that is designed to be a solution for energy inclusive housing. Furthermore, the convenience of connecting medium-scale consumers like shops or restaurants must be analysed.

- The microgrid should use distributed generation units with carbon-neutral production, whatever the surplus of electricity by residential PV used for the heat pumps is. Rather then installing local fossil fuel plants, the main grid should be preferably used as a backup, due to its carbon-neutral development.
- Flexibility should be provided to the main grid through the large-scale boilers, since they can be charged when electricity prices are low and shut down when prices are high. The microgrid can offer the controlling of this flexibility.

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