Soft-islanding a Group of Houses through Scheduling of CHP, PV and Storage

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Abstract—**In this paper we investigate the possibility of soft-islanding (near-autonomous operation) a group of houses from the electric power grid in the Netherlands. Energy balancing is possible through applying multi-mode smart grid scheduling for controllable energy generation, storage and consumption devices. The modeled neighborhood consists of modern, well-insulated terraced houses in a typical Dutch climate, each equipped with roof-mounted photovoltaic (PV) panels. The panels are sized to cover the daily electric demand during sunnier parts of the year where the heat demand is low. The system also includes a centrally placed combined heat and power (CHP) with hot water and electric storage, and controllable devices within the houses such as washing and dishwashing machines. The daily domestic hot water demand is supplied entirely by the central CHP. The investigation includes an estimation of system dimensions, e.g. PV, CHP and storage capacities based on daily supply and load profiles on top of the multi-level scheduling. Through simulations we demonstrate the technical feasibility for off-grid operation of this neighborhood.**

Index Terms—**Smart grid, Demand side management, Peak shaving, Flexible loads, Controllable loads, Off-grid**

I. INTRODUCTION

The use of traditional, hydrocarbon-based fuels from underground sources contributes to increasing carbon dioxide concentrations in the earth's atmosphere [1]. Most of the world's governments have recognized the need for energy savings and a transition towards energy generation from renewable sources, e.g., solar and wind energy and energy from biomass. The European Union developed legislation to reach energy saving and transition targets by 2020 (aka 20-20-20 goals: 20% energy saving, 20% renewable in 2020) and eventually a completely renewable energy system by 2050 [2]. Unfortunately, typical production hours of solar and wind energy do not fully match hours in which the demand occurs. This has lead to wide recognition that enabling-technologies such as battery storage and controllable electric devices are important to match the available energy from renewable sources with the demand [3].

A specific solution is a so-called smart controlled micro-grid, i.e., a low-voltage power grid which matches supply and demand locally, without causing peak loads on the larger distribution grid. This paper investigates the feasibility of a smart controlled micro-grid for a group of houses with the specific challenge to balance local energy supply with the demand of the houses as much as possible. The local energy system consists of roof-mounted PV installations and a community combined heat and power system (CHP) for the thermal demand (space heating and domestic hot water). These two types of generators are complementary to each other: peak production of PV during the summer months, and high usage of the CHP unit during the winter months when PV is not readily producing. As a consequence, besides a local, low-voltage power grid, there is also a local thermal grid from which space heating and hot water demand for each house are met. The CHP plant is placed centrally within the neighborhood, together with a thermal storage water tank. Each house has an electric battery and some controllable devices, e.g. a washing and dishwashing machine. The described micro-grid system with local generation and storage has the potential of operating almost independently of the main grid. Soft-islanding, rather than completely islanding, this microgrid system adds robustness to handle disruptions. The purpose of this paper is to verify the feasibility of such a system using the Triana Demand Side Management (DSM) methodology developed at the University of Twente [4].

There are three main contributions of this paper:

- A novel strategy to minimize imports of electricity from the grid
- A simulation of electricity grid independence through different heating seasons
- An initial capacity sizing methodology of distributed energy generation and storage systems for a neighborhood microgrid

II. RELATED WORK

Recently researchers from across the globe have been studying the possibility to control energy generation and consumption of houses or neighborhoods as part of a smart grid [5]. Some investigators focus on DSM strategies to minimize energy costs for residents or shave peak loads on the network, while other researchers focus on power quality and stability aspects of true islanded-operation of microgrids.

In [6], loads on a network are investigated in a peak-shaving strategy and energy-cost minimization strategy for residents. In [7], results are shown for short-term islanded operation of a single house, using a micro-CHP with electrical and thermal storage. In [8], a more complex residential energy system is investigated which contains PV, solar thermal, a CHP and a boiler as generators and thermal and electric battery storage. DSM with model predictive control is used to minimize energy costs for residents. The simulated results indicate up to

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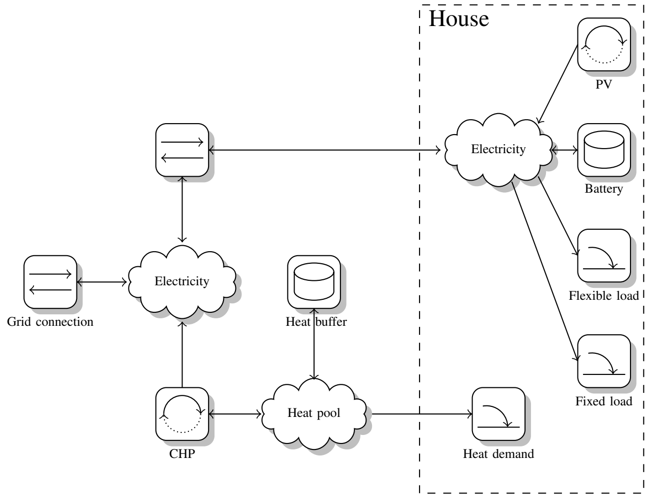


Fig. 1: Schematic representation of the neighborhood energy system.

30% cost reduction for residents. However, the optimization objective of minimizing energy costs for residents induces a frequent exchange of energy to the grid at times of high feed-in prices and from the grid at times of low energy prices. To reach near off-grid operation the goal is to minimize exchanges with the grid rather than just minimize time-of-use costs.

In [9], researchers investigate the capability of a decentralized microgrid for a residential area containing PV, wind turbines and electric storage to function independently from the main grid. The investigation considers only the domestic electric energy demand. This is also the case in [10], which reports on models for power generators to investigate power quality and loads within off-grid microgrids.

The research presented in this paper considers both generation and demand for electric *and* thermal energy within a small microgrid consisting of 16 houses. The purpose of this study is to reach near autonomous operation from the main electricity grid, also known as "soft-islanding". However, this energy system still needs a connection to a natural gas or local biogas fuel source. The main contribution to related work is the inclusion of thermal energy demand and generation combined with model predictive control to fulfill both electric and thermal demand.

III. METHODS

A. Model of the neighborhood

Figure 1 presents a schematic representation of the neighborhood energy system using the energy stream models described in [11]. The electric and thermal loads are modelled individually for each house and summed to represent the total demand of the community. In this model, 16 terraced houses are modeled. The controller aims to meet these demands while also leveraging local resources such as a hot water storage tank, time-shiftable flexible loads and a CHP plant. We investigate 5 different weeks to evaluate the seasonal effects on the system (see Table I). The following two sections discuss the modeling of each energy consumption and generation component.

TABLE I: Description of five test weeks

Week	**Month**	**PV Generation**	**Heat Demand**
4	Jan	Low	Very High
6	Feb	Low	High
26	June	High	Low
31	July	Very High	Low
43	Oct	Low	Medium

B. Electric loads

1) Uncontrollable devices: The static, inflexible electricity profile consists of two parts: consumption and production. In the model, each house is given a unique static consumption profile which represents the aggregated load of domestic devices such as lighting, electronics, ventilation, etc. The electricity consumed by the smart (controllable) devices such as dishwashers, washing machines and dryers is excluded. The fixed load profile is artificially generated based on smart meter measurements obtained in the Dutch field test in Lochem (see [12]). Profiles are generated based on occupancy, activities and age of persons in a household and are given in the average power consumption at 15-minute intervals. The resulting daily average electricity consumption per household is 7.6 kWh.

Electricity produced by the roof-mounted PV panels is calculated using the 2014 weather data measurements from the Twenthe measurement station and was provided by the national weather meteorological institute KNMI (Koninklijk Nederlands Meteorlogisch Instituut) [13]. This dataset provides the solar energy irradiation on a horizontal plane in hourly intervals. These values are linearly interpolated to match the 15-minute intervals used in the simulations. Calculations are then performed to estimate the direct and diffuse irradiation on a horizontal plane (see [14]), which are used to calculate the perpendicular irradiation on the PV panel [15]. Based on the efficiency of the setup (PV panels and inverter), this solar energy is converted to the corresponding electricity production. The final chosen parameters are given in Section V.

2) Controllable devices: Each house is assumed to own two time-shiftable devices: a dishwasher and a combined washing machine/dryer. The probability distribution profiles of start times for shiftable devices come from the Smart-A project [16], which consists of extensive surveys on when residential devices are used. The probability profile of startup times for each device in each house is assumed to follow the overall European profile. Delay times (expressing flexibility) are also derived from the Smart-A project. The actual energy use of each device is as given in the report. Combined with the static electricity profile, this results in a total electricity consumption of 10.2 kWh per household per day on average.

C. Thermal loads and system dimensions

In Figure 2 the aggregated thermal demand of the neighborhood is shown as the monthly (bars) and daily (line) total energy demand. The thermal heating demand is based on data for space heating and domestic hot water demand. For space heating, data are obtained by simulations, using approximate thermal models for the space heating demand [17]. Each house has, on average, a thermal demand of approximately 28 GJ per year of which 18 GJ is for space heating and 10 GJ is for

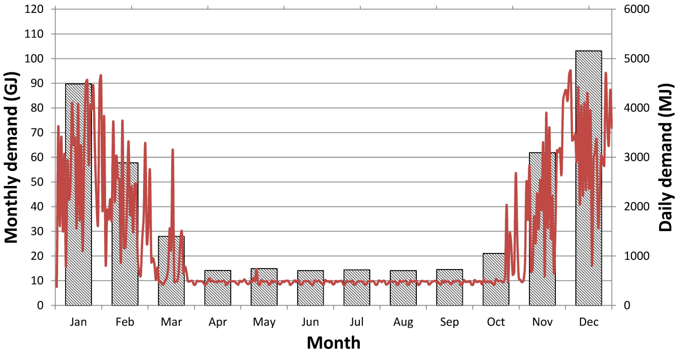


Fig. 2: daily and monthly total thermal demand

domestic hot water. For domestic hot water, data are obtained from slightly randomized demand patterns for each household. The size of the CHP plant and thermal storage system is described in section III-E

D. Optimization approach

1) Flexible Appliance Scheduling: To schedule the appliances we use the profile steering methodology introduced in [18]. The optimization implementation steers the energy use towards a desired profile, i.e., the methodology attempts to minimize the difference between a desired profile and the realized profile. The methodology works hierarchically and in two phases. In the initial phase, the controller requests each appliance to construct a schedule following the desired profile as much as possible. Then the scheduled profiles are aggregated and the result is compared to the desired profile. In the second iterative phase, each appliance is then asked to construct a new, candidate schedule which best compensates for the deviations between the aggregated scheduled profile and the desired profile. In each iteration, the appliance with the candidate schedule that best achieves the desired profile is picked. This appliance then updates its schedule to match the candidate schedule. The results presented in [18] show that, for a test case of 121 houses, the methodology significantly lowers the peak load and keeps voltages within legal bounds. To reach soft-islanding, the desired profile in this paper is set to a zero profile, meaning that the objective is to minimize import and export of electricity. For more details on and a precise mathematical formulation of the optimization strategy we refer the reader to [18].

2) Optimization Test Cases: Three strategies are evaluated using the simulated electricity and heat demand data and applying optimization using ideal predictions of demand and weather forecasts to schedule the flexible devices.

i - Base Case (BASECASE) In the first case, no electricity storage system is implemented. Heating demand is simply met through scheduling of the CHP and maintenance of the thermal energy storage. Additionally, the CHP is scheduled such that it minimizes changes in operational state. Practically, this could be achieved by parallel operation of several smaller CHPs that each have a limited operational range. Because the size of the demand can be very large, occasionally energy must be drawn from the grid. Otherwise the size of the CHP system would be too large.

ii - Optimal Control (CON) In the second strategy, the controller decides the start times of the time-shiftable devices and the operation of a thermal water tank. The optimization strategy of the controller is to flatten the energy profile for the community of houses such that there is zero or nearly zero energy withdrawn from the grid.

iii - Optimal Control with Electricity Storage (CON/BAT) In the final situation, scheduling of domestic appliances is implemented, but additionally each house is given a battery storage system as a resource. The community also has a thermal water tank. In the overall scheduling strategy, the accumulation of the batteries acts as a community resource and is used to further flatten the energy profile and minimize dependence on the electric grid.

E. Sizing the system

The size of the CHP plant and the thermal storage system can be determined by analyzing the highest thermal demand pattern. In this test case, CHP size will be chosen to support mono-operation without a supporting boiler. From the demand seen in Figure 2, the required output of the CHP is chosen to be 60 kW thermal and 30 kW electricity in combination with a 250 kWh hot water tank. During periods of low Pv generation, the CHP plant will produce most of the electricity. It is beneficial to choose a CHP design which has a heat/electricity production ratio close to the heat/electricity demand ratio as these are synchronized. This can be seen as a practical rule of thumb for these systems.

After the size of the CHP is determined, the size of the PV setup is determined. Using the models, the electrical energy demand after optimizing the CHP operation and shifting loads is obtained. This results in an inflexible electricity consumption profile. The deficit of electric energy has to be provided by the PV panels. Sizing of the PV panels is determined taking into account the following constraints on the arrangements of the houses: half of the PV panels are facing south, 25% are facing west and the other 25% are facing east, all at an angle of 35 degrees. The efficiency of the PV panels is set to 16%, which corresponds to PV systems currently on the market.

As this project aims for a “soft-islanding outcome”, we accept a maximum daily electric energy deficit of 1 kWh per household. With these values, constraints and models, we found that a minimum total of 15 m^2 PV panels are required to satisfy this constraint. This size is required to the meet the demand of a worst-case day in week 43, in which the solar irradiation and heat demand are relatively low. From an electricity production perspective, this is the worst-case scenario and hence the PV setup is sized according to this week. On higher PV generation days, any excess generation after optimization is sent to the grid.

In order to allow for a soft-islanding operation, batteries are required to add more flexibility to match the electricity production and consumption. With the CHP and PV sized, the electricity consumption profile is obtained. The shortage of electric energy is determined by accumulating the power consumption (or production) and finding the largest difference between a local minimum and local maximum. This difference indicates the amount of energy that has to be shifted and hence the size of the battery storage. Using this method, we find a total capacity of 30 kWh for week 43, which is the worst-case scenario. As a result, we choose to equip each house in the model with a 2 kWh battery, which brings the total capacity to 32 kWh. The battery storage dimension is relatively small, which is a result of the intelligent operation of the CHP to produce electricity in the evening. Therefore, it is not necessary to store all electricity produced by the PV system.

As a result, these are the values used for the system:

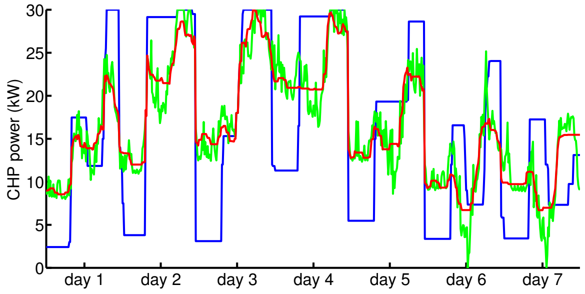
- CHP with 60 kW thermal/30 kW electricity
- 250 kWh buffer connected to the CHP (CON and CON/BAT), 50 kWh for BASECASE
- 15 m^2 of PV panels per house
- 2 kWh battery storage per household (CON/BAT), 0 kWh (BASECASE and CON)

IV. RESULTS

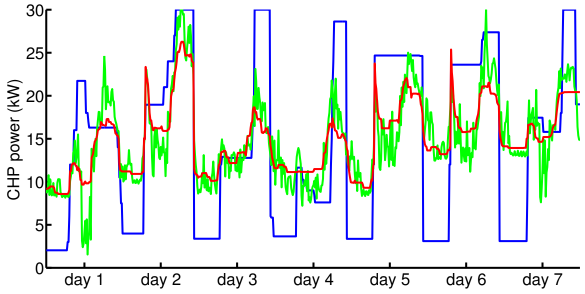
Figure 3 shows the CHP power production for five separate weeks. These weeks are chosen to represent different extreme situations for heating demands and PV production. For explanation, Table I gives an overview of the differences in the weeks.

During winter (weeks 4 and 6) CHP production is driven primarily by heating demands for the community. In the base case (BASECASE), operational changes are driven by the constraints on meeting heating demand and minimal changes to the operational state. Both the control (CON) and control/battery storage (CON/BAT) strategies operate less often at extremes in CHP production when compared with BASECASE. This is because the systems efficiently utilize the thermal storage. The total energy demand of the system is equal in all three evaluated cases. The difference in the CON and CON/BAT profiles is the ability to shift electric loads to reduce peak loads compared to the base case. The additional benefit of battery storage in the CON/BAT case is able to smooth the demand profile even further, which is healthier for the operation of the CHP. During week 4, the worst-case scenario for heating demand, the system is still able to meet all demands of the microgrid despite low PV production. Because this is the limiting constraint on CHP size, additional strategies to pre-heat houses during winter months could lower the required CHP capacity. During summer weeks the CHP operates only for a portion of the day in the evening because there are minimal heating demands and the combined PV systems are able to acquire enough energy to meet the remaining electricity demand. It should be emphasized that the CHP production in the CON and CON/BAT cases has been scheduled in a way that will minimize the amount of energy drawn from the larger electric grid. Although the BASECASE appears to have a flat operational profile, the resulting effect on the grid will have larger fluctuations as shown in Figure 4.

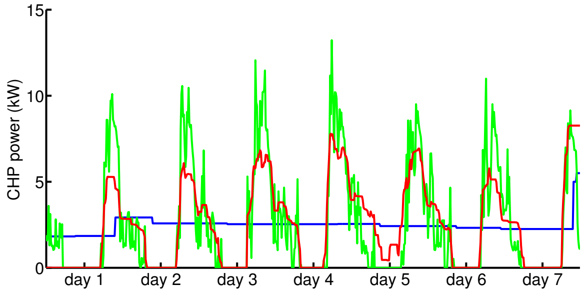
Figure 4 shows the total power required from the grid. Negative values indicate energy exports to the grid. In the ideal microgrid case, no power is required from the grid even during difficult days with high heating demand and low PV production. In the BASECASE, the current size of the CHP system is simply not able to meet all electric demands and thus requires power



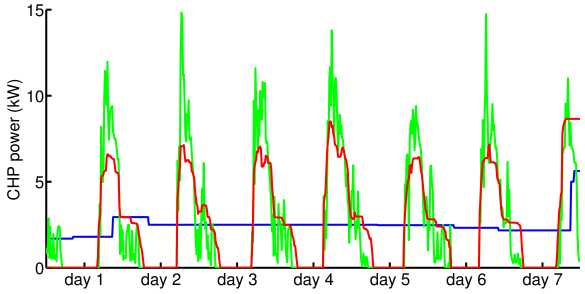
(a) Week 4



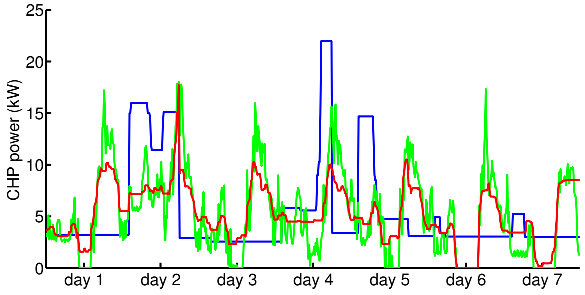
(b) Week 6



(c) Week 26

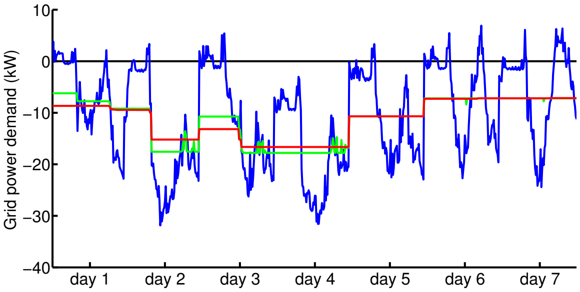


(d) Week 31

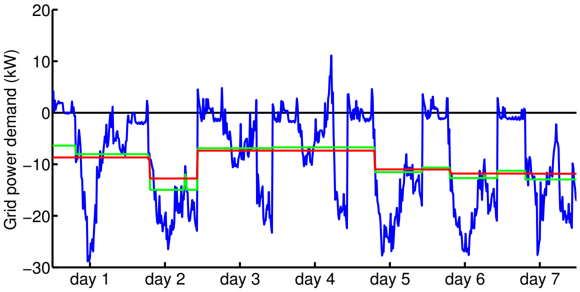


(e) Week 43

Fig. 3: CHP electric power production for five test weeks, ▬ BASECASE ▬ CON ▬ CON/BAT



(a) Week 4



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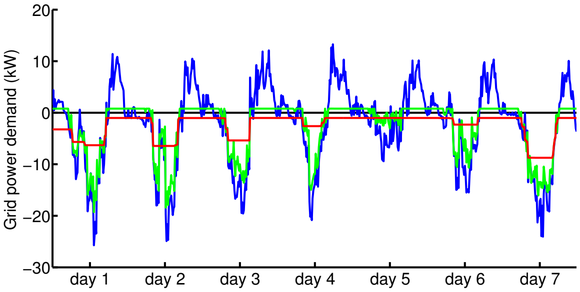

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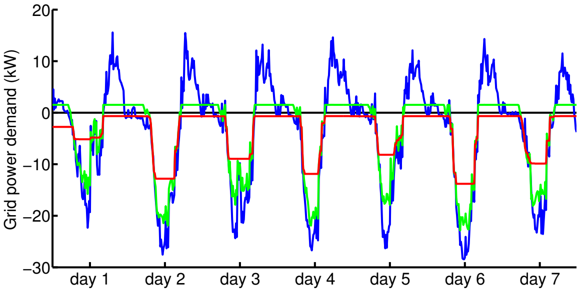
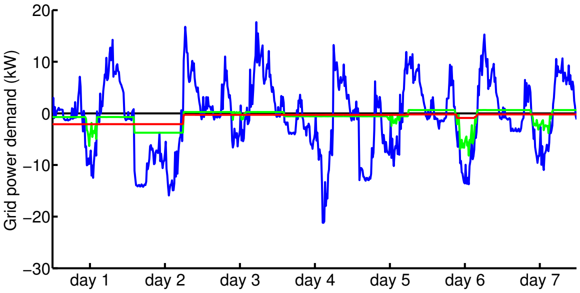


(d) Week 31



(e) Week 43

Fig. 4: Grid power demand for five test weeks, ▬ BASECASE ▬ CON ▬ CON/BAT

from the grid. The operation of the CHP in the BASECASE does not encourage a flat grid profile as seen in the large variation in electric demand and supply. During winter months there is a higher heating demand while electric energy demand of the neighborhood remains moderate. Therefore in the CON and CON/BAT cases, the neighborhood is actually able to export a moderate amount of electricity back to the grid that would otherwise be wasted. Though electric independence is an ideal case, soft-islanding, where the microgrid can still interact with the larger electric grid, would be needed to maximize utilization of excess solar energy. One benefit of the control strategy is that it creates a predictable load. Rather than the BASECASE with large swings in demand, the CON cases both have very flat loads, which are more manageable to meet, due to the controlled devices. Were this microgrid to interact regularly with the larger electric grid, it could be done in a predictable and consistent manner. Overall, during the other weeks the CON case will withdraw a minimal amount of energy from the grid (1 kW) and the CON/BAT case will export a minimal amount of energy to the grid (1 kW).

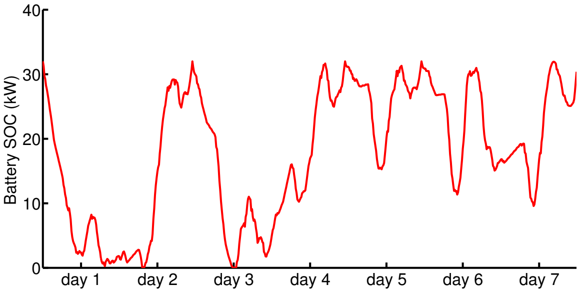
Figure 5 shows the operation of the battery in the CON/BAT case. The data indicate that the batteries are used daily and to their full extent in the summer weeks (Figures 5c, 5d) while they are used partially and less frequently in the autumn and winter weeks (Figures 5a, 5b, 5e). This is primarily because in the autumn and winter weeks the heating demand already requires near continuous operation of the CHP (figure 3), which generates electricity as a byproduct. In the summer weeks electricity is generated by PV panels during the day, and partially stored in the batteries. Electricity consumed during the night is provided by the battery.

The optimization did not take into account restrictions on energy withdrawal rates and state of charge. Depending on the type of battery, these restrictions can greatly improve and extend battery life, or be necessary for the safe operation of the battery. Including such restrictions in the simulation could result in the need for more battery storage per household.

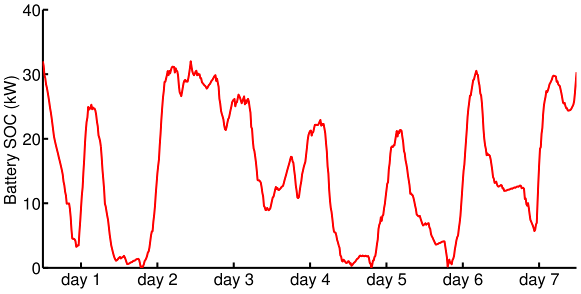
V. CONCLUSIONS

In this evaluation, with optimal control, community shared resources are able to function as a microgrid. The strategy is able to function during both heating and cooling seasons while remaining electrically self-sufficient. The model and optimization functioned on 15-minute intervals to minimize imports of electricity to the grid. One finding is that with such a system, the size of an expensive battery storage system can be kept relatively small as the CHP with heat storage tank already provides a lot of flexibility to produce electricity during the evening. The CHP therefore works in tandem with the PV production. Furthermore, for the microgrid to function independently, the heat/electricity production ratio of the CHP should be close to the consumption ratio during the colder months of the year. Finally, it should be noted that, especially during periods of high solar irradiation, there were significant exports to the grid.

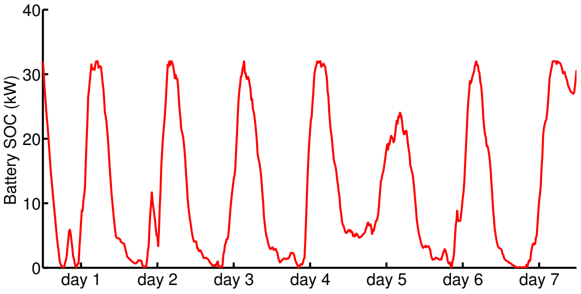
Although in this case study we do not provide a solution for the surplus power, our future work aims to address this problem. For the micro-grid, this strategy is able to create a relatively smooth profile for the CHP operation while still meeting



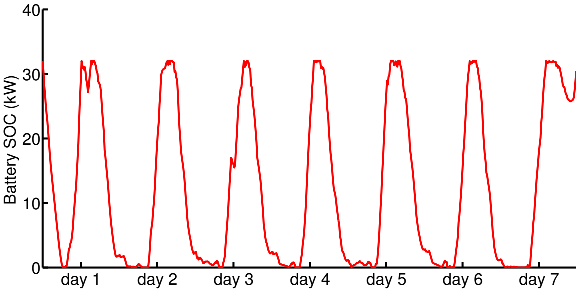
(a) Week 4



(b) Week 6



(c) Week 26



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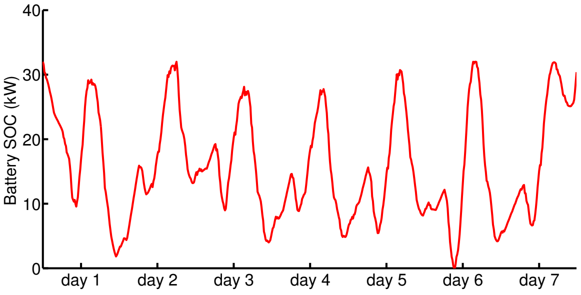

(e) Week 43

Fig. 5: Battery state of charge for five test weeks, — CON/BAT

the heating and electricity demands at all times. Although microgrids may be an opportunity for residential neighborhoods in the future, this research demonstrates that there will be a need for an optimization strategy that will leverage energy resources in order to reduce the capital costs of installing such a system. Future work for this group aims to incorporate additional energy technology such as vehicle-to-grid. Further investigation may focus on creating predictable electricity loads for a micro-grid that partially interacts with the grid during peak hours.

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