Islanded house operation using a micro CHP

Albert Molderink, Vincent Bakker, Johann L. Hurink, Gerard J.M. Smit

Department of Computer Science
University of Twente
P.O. Box 217, 7500 AE,
Enschede, The Netherlands
email: a.molderink@utwente.nl

Abstract— **The μCHP is expected as the successor of the conventional high-efficiency boiler producing next to heat also electricity with a comparable overall efficiency. A μCHP appliance saves money and reduces greenhouse gas emission.**

An additional functionality of the μCHP is using the appliance as a backupgenerator in case of a power outage. The μCHPcould supply the essential loads, the heating and reduce the discomfort up to a certain level. This requires modifications on the μCHP appliance itself as well as on the domestic electricity infrastructure. Furthermore some extra hardware and a control algorithm for load balancing are necessary.

Our load balancing algorithm is supposed to start and stop the μCHP and switch off loads if necessary. The first simulation results show that most of the electricity usage is under the maximum generation line, but to reduce the discomfort an electricity buffer is required.

Keywords—**μCHP, islanding, load balancing**

I. Introduction

People become more and more aware of their energy usage, due to rising energy prices and a growing awareness of the greenhouse effect. Because of the rising energy prices, customers are willing to spend more money for energy-saving solutions, such as high-efficiency boilers for house-warming. More money is available for researching new, more energy efficient technologies and alternative energy resources.

One of the new developed, energy-saving and market ready technologies is the micro Combined Heat and Power (μCHP) [1]. μCHP is seen as the successor the conventional high-efficiency boiler. It produces not only heat but also electricity with an overall efficiency comparable to a high-efficiency boiler.

For an easier market introduction, producers of μCHP appliances and electricity suppliers are looking for additional functionalities for μCHP appliances [1]. One possible additional functionality is using the μCHP as a backup generator is case of a power outage.

An power outage does not only lead to discomfort caused by not working appliances, but can also lead to safety and security issues. Safety systems and security systems require electricity for proper functioning. Most of these systems have their own backup supply (mostly a battery), but these supplies are only for a limited time. In case of a longer outage, these systems require an external supply. Another effect of power outage is the failure of central heating, even if the house is heated with natural gas. The waterpump that pumps the water through the radiators requires electricity.

A μCHP appliance could be, with some changes and additions, capable of producing energy when the main supply fails. For safety reasons and to keep the produced electricity within the house, the house has to be decoupled from the grid [2]. This is called islanding.

When the μCHP is used as a backup-generator, it could supply at least the safety and security systems and the natural gas fired central heating. Next to the supply to these systems, a limited number of appliances can be supplied to reduce the discomfort. A μCHP does not provide enough electricity for all appliances so the generation and load have to be balanced.

This paper describes the requirements of a system in which a μCHP appliance functions as a backup-generator. These requirements comprise changes to the appliance itself, changes to the domestic electricity infrastructure and nescessary algorithms. Furthermore the first simulation results of the generation/load balancing algorithms are presented.

Section II gives a more detailed description of μCHP appliances. Afterwards the domestic electricity usage is studied. Section IV gives a describtion of an islanded house and its requirement. In section V a description of the used simulation method and models and the first results are presented. The last section concludes this paper.

Technology	Efficiency		
	total	electricity	heat
Stirling	95%	15%	80%
Rankine	75%	15%	60%
IC	80%	20%	60%
Fuel cells	77%	30%	47%
Gasturbines	85%	18%	67%

TABLE I
Relation between electricity and heat efficiency for the μCHP technologies, based on low (or net) heat of combustion

II. μCHP appliances

A μCHP appliance produces less heat per consumed amount of fuel (mostly natural gas), but the energetic sum of the produced heat and electricity is comparable to the produced heat per amount of fuel of a conventional high-efficiency boiler. Replacing a high-efficiency boiler with a μCHP leads to a higher natural gas usage, but because the μCHP produces also electricity, the netto electricity import reduces. The economical advantage for the house owner is that electricity is more expensive than natural gas, the total energy bill decreases. An average Dutch family can save € 200 every year (based on a Whispergen^{TM}, see description below) [3].

The environmental advantage of μCHP appliances is the significant higher efficiency compared with power plants. During the production of electricity out of fossil fuel also heat is produced as a byproduct. In power plants this heat is (mainly) lost energy. In μCHP appliances this heat is used for heating the water in the boiler. Only a part of the used natural gas in the μCHP appliance is used purely for the production of electricity, the rest of the natural gas is used for the heating of the water (although technically seen it is lost for electricity production). Conventional power plants have an efficiency of at most 55% [3], μCHP appliances have an overall efficiency of 90%. Both percentages are based on low (or net) heat of combustion. Because the electricity produced by the μCHP is produced with a higher efficiency, the total used energy is reduced. An average Dutch family saves about 1000kg carbon dioxide every year by installing a μCHP appliance as replacement of a conventional high-efficiency boiler [3].

The μCHP appliances can be based on a number of technologies, for example Stirling engines, Rankine engines, fuel cells, gasturbines and internal combustion (IC) engines [1], [3]. The different technologies give different ratio between the heat and electricity production (see Table I, which is based on [1], [3]). Today, only μCHP appliances based on Stirling engines are commercial available, the other technologies are still in research or development stage.

The μCHP used for this research is the WhisperGen^{TM}, althoug the methods are applicable for other (types of) μCHPs. The WhisperGen^{TM} is a μCHP based on a Stirling engine. The electrical producing capacity is approximately 1.0kW, with a maximum peak production of 1.2kW (when the appliance is started it can generate a peak). The heat producing capacity is 8kW. The overall efficiency is 90%. The heat capacity can be increased with an extra top-up (high-efficiency) burner, but this is without electricity production. Because of the mechanical properties of the Stirling engine, the μCHP production can not be controlled (only on or off).

III. Domestic electricity usage

There is little information publicly available about individual domestic electricity usage. Only the electricity usage of a group of users is available (neighbourhood, city or country). All peaks in the usage caused by individual appliances in a house are levelled out because of the averaging over multiple houses. However, this specific information is essential to develop and simulate load balancing algorithms, to be able to simulate turning off appliances.

Figure 1 shows the (measured) electricity usage of a house with a typical high-demand [4]. The total electricity usage of the showed day is ≈20kWh, the average electricity usage for a Dutch family is ≈9kWh [5], for an UK family ≈13kWh [6]. The differences between the average usage and the measured usage are mainly caused by the higher constant load (≈500W) in comparison to the known averages and generated usage profiles [7], [8]. The peaks are not higher and have the same shape.

A. Peak usage

The peaks in the electricity usage define the required capacity of the power plants. Therefore, peak reduction is an advantage for the electricity suppliers. Using a μCHP appliance can reduce peaks by scheduling the runtime in such a way that it produces electricity during peaks [9].

Peaks can also be reduced by cutting off some loads (load shedding) or shift loads to non-peak times (load

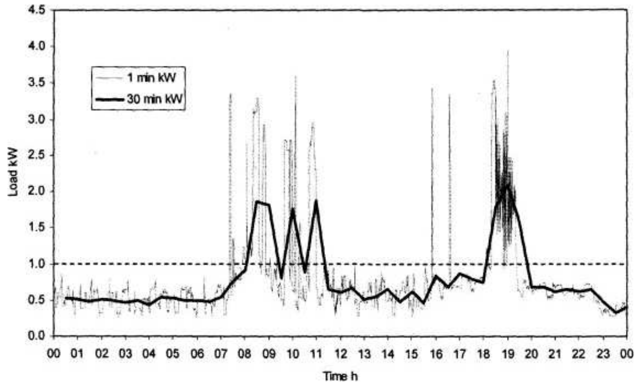


Fig. 1. Load profiles for a single December weekday for a house with a fairly typical high-demand

shifting). These load balancing algorithms can be used when there is only a limited amount of electricity available, for example when during a power cut a generator supplies a part of the electricity (the generator has limited capacity). Another application for load shedding algorithms becomes important when demand-driven electricity prices are introduced [10], [11]. An example of this demand-driven prices is that the first 2kW is cheap. When the usage is higher than 2kW the price raises. In such a pricing system it is attractive to avoid peak usage for house owners. One reason for this demand-driven prices, from the standpoint of the utility company, is that the purchased electricity during peaks is very expensive (while costumers presently pay a fixed price) [10]. A second reason is that the peaks cause a lower efficiency of the power plants. The capacity of the plants is based on the peak usage, the rest of the day they are running in a low, less efficient mode, resulting in a higher CO2 emission [12].

IV. Islanded House Operation

Supplying electricity by a backup generator during a power outage is called Islanded House Operation because the house acts as an island: the house produces its own electricity while it is decoupled from the grid, it is an electrical island. The aim of the research is to develop a prototype in which a μCHP unit operates as an islanded generator, supporting at least the critical electrical loads in the house and supporting heating requirements. Three different scenarios of a power outage are defined:

- a short power outage (<10 minutes)
- a longer outage (<4 hours)
- an extended interruption to the supply (several days)

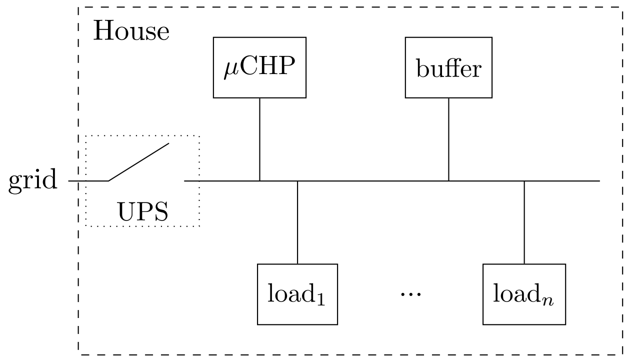
To create an islanded house in general and an islanded house based on a μCHP in particular, a number of challenges are raised:
1. Detect the power outage and start the μCHP when it is not already running.
2. Decouple from the grid.
3. Maintain the supply (partly) without interruption, also during the time the μCHP is starting up and produces no electricity yet (using an Uninterrupted Power Supply-UPS), maximal ten minutes for a WhisperGen$^{\text{TM}}$.
4. Balance the generation and load. An algorithm that decides which loads are supplied and when the μCHP is running. Furthermore the possibility to control the μCHP and to switch off appliances.
5. Be able to shut off the appliances that have to be shedded.
6. Modify the μCHP appliance so it can produce 230V/50Hz standalone and it can get rid of its heat surplus; Current μCHP appliances require the 50Hz of the grid as reference to maintain at 50Hz. The appliance can only run when it can get rid of its heat.
7. Synchronise with and couple to the grid once the electricity supply is re-established. The domestic electricity production must be in phase with the grid before it can be coupled back to the grid.

A. Generation/load balancing

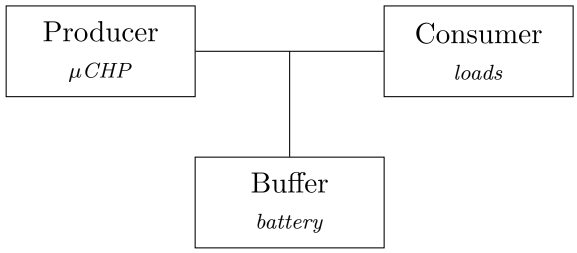
In the first stage, the research is focussed on load and generation balancing, including the control algorithms for the hardware. The produced and consumed electricity has to be in balance all the time [13]. Differences between the produced and consumed electricity can be solved with an electricity buffer (till a certain limit), for example a battery [13].

The domestic electricity infrastructure for a house with islanding capabilities can be modelled as shown in Figure 2a. It consists of a connection to the grid, an UPS that decouples and couples the house from and to the grid, a μCHPappliance, an electricity buffer and a number of loads. The total system in islanded operation mode can be modelled as a producer, a consumer and a buffer with a limited capacity. The producer is the μCHPappliance, the consumer represents the accepted load. This simplified model can be used for the load and generation balancing algorithms. These two models are schematic given in Figure 2.

According to the measured energy usage given in Figure 1, most of the time the total load of a household is much lower than 1kW (the capacity of the



(a)Schematic of the electrical architecture of a house with islanding possibilities



(b)Schematic of house in islanded operation

Fig. 2. Schematic of electricity system in a house with islanding possibilities

Whispergen$^{\text{TM}}$), even for a house with a typical high-demand load profile. However, the electricity usage during peak hours is much higher than 1kW.

During low-demand times the μCHP produces more electricity than is consumed and the system must cope with this electricity surplus. Till a certain limit, the electricity can be stored in the electricity buffer. When the buffer is full, another way of getting rid of the electricity is required or the μCHP appliance must be switched off. The electricity is then temporarily supplied by the electricity buffer. In that case, the buffer must be big enough to supply electricity for a significant time, because the μCHP requires a cooldown time before it can be restarted again (technically a couple of minutes, but the lifetime of a Stirling engine is defined by the number of starts).

During high-demand, the μCHP appliance does not generate enough electricity to supply all loads. When the electricity buffer is not empty, (a part of) these loads can be supplied by the electricity buffer. But it is probably not possible to supply all loads during the peaks: batteries with such a high capacity are very expensive and bulky. Therefore, the system must be able to switch off or shift loads.

The algorithm to decide when the μCHP appliances is switched on/off and which loads are supplied, has at least as considerations:

- The generation capacity of the μCHP
- How long the μCHP is running or switched off and its cooldown time
- The profile of the loads
- Electricity buffer capacity
- State of the electricity buffer

To be able to decide correctly which loads are to be shedded or shifted, some more information about the loads is required. Without extra information it is impossible to make an algorithm that supplies the required loads. The loads have for instance a certain priority; the goal of the islanding is to supply at least the safety and security systems.

If the electricity buffer is not used for extra supply of loads, it is not even possible to make coffee or tea: a coffee maker and watercooker use both more than 1kW. On the other hand a μCHP appliance can generate 24kWh electricity each day (24 hours of 1kW). The agregated electricity usage of Dutch and UK families are respectively 9kWh and 13kWh per day. So, a μCHP can produce much more electricity than required: when the electricity buffer has enough capacity and is fully loaded it is possible to supply all loads. Because a battery with a high capacity (most usefull electricity buffer today) is very expensive, big and heavy [14], it is a consideration between the level of discomfort during a power cut and the capacity of the battery.

V. Simulations

For studying the generation/load balancing algorithms a model is defined in Matlab. The model consists of three components: production, buffer and consumption (see Figure 2). The production component comprises the netto electricity production, the buffer component models the capacity, state of charge (SoC) and charge/discharge characteristics of the battery. The consumption component consists of the total electricity demand, the load balancing algorithm and therefore the supplied loads.

The simulation results described in this section encapsulates only simulations of load balancing algorithms without extra supply from the buffer. The maximum supply in the algorithm is just set to a maximum of 1kW, because current the models for the production and the buffer are not accurate enough.

A. Simulation model

In the operation of the appliance four different stages can be observed: off, starting up, running, stopping. When the appliance is starting up, it requires

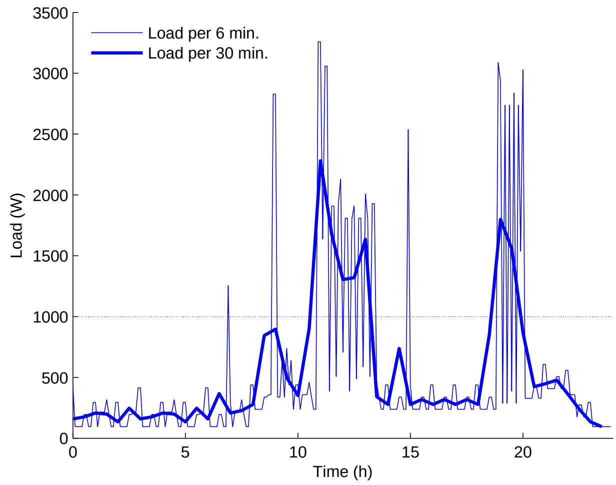


Fig. 3. Defined domestic electricity usage profile

electricity to start the Stirling engine and gas for preheating the Stirling. The running stage is the normal operational stage, the μCHP produces electricity and heat using natural gas. In the stopping stage, the appliance uses no gas, but it uses electricity to stop the engine in a proper way. For the model these four stages are defined, where the starting and stopping stage have a negative electricity production.

The buffer model is based on a battery. The maximum capacity of the buffer is modelled as constant, the SoC is a function of the initial SoC and the charge/discharge functions. In the first model it is assumed that there is no leakage, the SoC does not change if there is no charging and discharging. This assumption is based on the simulation time of one day. The charging of the battery is modelled as increasing the SoC with 60% of the electricity surplus (approximately the efficiency of a battery in this situation [15]). Discharging the battery is modelled as decreasing the SoC with the supplied electricity (no loss). In charging/discharging the battery the maximum charge and discharge currents and the current dependencies of the charge/discharge characteristics are not taken into account (e.g. the efficiency depends on the currents [15]). For initial simulations the model is sufficient, but requires improvements.

To be able to define a model for the consumer, a domestic electricity usage profile split up into appliances is required. Therefore, an usage profile is generated based on the usage patterns of many-used appliances. A bottom-up approach comparable to [8] is combined with statistical information from [12], [7]. First the usage patterns of the used appliances are defined, based on [11], [12] and measurements with an energy usage meter (Voltcraft® Plus Energy Monitor 3000). Next is defined when each appliance is used. The resulting total usage profile of a house is shown in Figure 3. The usage per appliance as function of time is available for the simulation.

The electricity usage of this profile is 13kWh, significant less than the usage of the earlier mentioned fairly typicial high-demand profile. It is more than the average Dutch usage and equal to the average UK usage.

The load balancing algorithm determines based on the generated electricity and the SoC of the buffer which loads can be supplied. These algorithms can be extended and improved by using more information for the decision which loads are supplied, for example using load priority or knowledge of the profiles to forecast the demand. The first versions of the algorithm does not use this extra information.

According to [4] a time averaging of the electricity usage of five minutes is a good settlement between precision and data quantity for on-site generation simulations. Time averaging is measuring the usage during a certain time interval t and divide this usage by t:

$$P_a = \frac{\int_0^t W(t)dt}{t}$$

Time averaging has a great influence on the peaks in electricity usage, a time averaging of 30 minutes flattens almost all peaks (see Figure 3). For the profile generator a time averaging of six minutes is chosen. This is almost the same granularity as the recommended five minutes and exactly one-tenth of an hour. Time slices of one-tenth of an hour are easier to model and therfore it is easier to define the times when the appliances are used. For example, using an appliance for half an hour with six minute time slices leads to five slices.

B. *First simulation results*

The results of the first simulations are based on six minute time slices. The generation and battery are part of the model, but do not (yet) influence the consumer. The consumer takes the 1kW upper bound into account for the load balancing.

The first simulation is a rather non-realistic simulation. The total load is cut off at 1kW, independent of the appliances. This simulation is performed to determine which part of the electricity demand is under the 1kW line. This is an indication of the amount of electricity consumed in the peaks above the 1kW line.

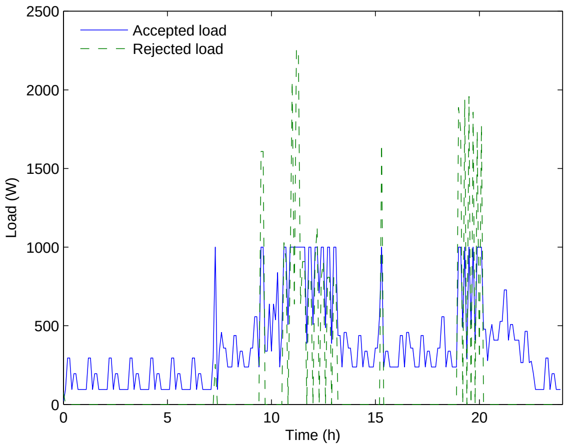


Fig. 4. Electricity demand cut off at 1kW

In other words: determine the demand that can not be supplied without extra supply from the buffer.

The result of this simulation is shown in Figure 4. The simulation shows that 70% of the total electricity demand is under the 1kW line. For the fairly typical high-demand profile it is even 80%. The simulation shows that a minor part of the electricity usage is consumed in the peaks. This part of the usage can be supplied with the electricity buffer, so the simulation gives an idea of the required capacity of the buffer in order to supply all loads.

The second simulation is a more realistic simulation. When the total load is higher than 1kW loads are shed. When the load of an appliance is shed, the starttime of the appliance is delayed. So, in the next time slice it is once again determined wether the appliance can start. In the same way the re-start of an appliance is shifted when the appliance is switched off in the middle of its runtime. There are as many loads shedded until the resulting load is lower than 1kW, starting with the biggest load. This algorithm is a combination of load shedding and a primitive form of load shifting.

The result of this simulation is shown in Figure 5. The simulation results show that more than 50% of the loads can be supplied by this algorithm. This second simulation demonstrates that is not realistic that a large factor of the theoretical available generation capacity of the μCHP can be used in practice (without buffer). With an electricity demand just above 1kW, a whole appliance is shedded.

VI. Conclusions and future work

To develop a μCHP unit operating as a backup generator in an Islanded House, modifications on the μCHP itself and on the domestic electricity infrastructure are required. Furthermore extra hardware is required to decouple from and couple to the grid and to maintain the supply until the μCHP appliance is producing electricity (with UPS functionality). During the power outage a load balancing algorithm balances the generated and consumed electricity. Differences between the generation and consumption can be solved (up to a certain limit) with an electricity buffer.

The first simulation results show that a significant part of the electricity can be supplied with an usage limit of 1kW. On the other hand, some elementary appliances like coffee machines use already more than 1kW. To supply also (some of) these appliances, electricity from the electricity buffer can be used. When the electricity buffer has enough capacity, it is possible to supply all loads. Because buffers with a large capacity are expensive and bulky, it is a settlement between buffer capacity and level of discomfort (i.e. the number of supplied appliances).

A. Future work

The buffer model has to be improved. Next the buffer can also be used for the electricity supply. The load balancing algorithm can be modified so it takes also the buffer SoC into account. Next, the priority of the loads has to be added.

Based on simulations with this improved models can be determined how big the battery should be for certain conditions (μCHP characteristics, discomfort level).

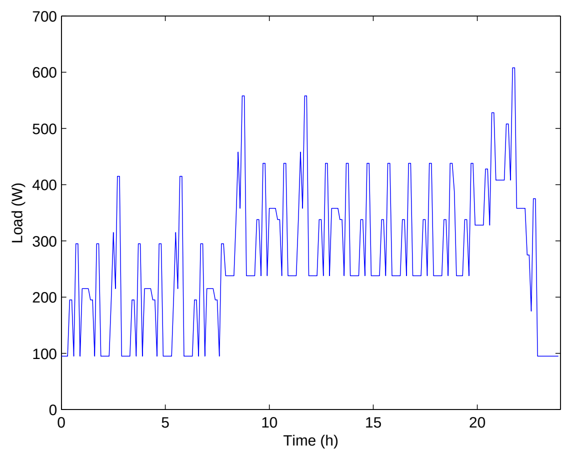


Fig. 5. Electricity demand lowered to 1kW by shedding appliances

When the requirements for the modifications of the μCHP and the domestic electricity infrastructure are defined and the challenges are tackled, a prototype can be build. With this prototype the simulations of the algorithms can be verified.

ACKNOWLEDGMENTS

This research is conducted within the Islanded House project supported by E.ON UK.

References

[1] Results of the Micro-CHP Technologies Roadmap Workshop. The micro-chp technologies roadmap. *United States Department of Energy*, page 26, December 2003.

[2] P.G. Cradinal. Applicability of co-generation equipment as a source of standby or emergency power. In *Industrial and Commercial Power Systems Technical Conference*, pages 62–68, May 1998.

[3] Arjen de Jong, Ernst-Jan Bakker, Jan Dam, and Hans van Wolferen. Technisch energie- en CO2-besparingspotentieel in Nederland (2010-2030). *Platform Nieuw Gas*, page 45, Juli 2006.

[4] Andrew Wright and Steven Firth. The nature of domestic electricity-loads and effects of time averaging on statistics and on-site generation calculations. *Applied Energy*, 84(4):389–403, April 2007.

[5] I.G. Kamphuis. E-box. een 'residential gateway' voor kostenbesparing en duurzaamheid. *Energieonderzoek Centrum Nederland ECN, Petten (Netherlands)*, January 2003.

[6] `http://www.npower-renewables.com/earlshall/index.asp`.

[7] Runming Yao and Koen Steemers. A method of formulating energy load profile for domestic buildings in the uk. *Energy and Buildings*, 37(6):663–671, June 2005.

[8] A. Capasso, W. Grattieri, R. Lamedica, and A. Prudenzi. A bottom-up approach to residential load modeling. *IEEE Transactions on Power Systems*, 9(2):957–964, May 1994.

[9] A.D. Peacock and M. Newborough. Controlling micro-chp systems to modulate electrical load profiles. *Energy*, 32(7):1093–1103, July 2007.

[10] Wei Zhang and A. Feliachi. Residential load control through real-time pricing signals. In *Proceedings of the 35th Southeastern Symposium on System Theory*, pages 269–272. IEEE, March 2003.

[11] M. Newborough and P Augood. Demand-side management opportunities for the uk domestic sector. In *IEE Proceedings Generation, Transmission and Distribution*, volume 3, pages 283–293, May 1999.

[12] Deering S., Newborough M., and Probert S. D. Rescheduling electricity demands in domestic buildings. *Applied Energy*, 44(1):1–62, 1993.

[13] E. Santi, D. Franzoni, A. Monti, D. Patterson, F. Ponci, and N. Barry. A fuel cell based domestic uninterruptible power supply. In *IEEE Applied Power Electronics Conference and Exposition*, page 605. IEEE, 2002.

[14] E.R. Furling, M. Piemontesi, P. Prasad, and D. Sukumar. Advances in energy storage techniques for critical power systems.

[15] J.W. Stevens and Corey G.P. A study of lead-acid battery efficiency near top-of-charge and the impact on pv system design.