MORE MICROGRIDS – Advanced Architectures and Control Concepts for More Microgrids”

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Contents

1. Introduction

This document provides a review of the requirements specification for controlling Microgrids meeting three objectives

a) To review fhe control functions developed in the Microgrids project for Operation Optimization and Centralized Control of Microgrids using the software for MGCC
b) Present energy balance methodologies in the literature and how cat these be adapted and applied in Microgrids
c) Provides suggestions for further research in the control specifications for the More Microgrids project.

In more detail, a description of the steady state environment is provided at section 2 and the following control functions developed in the Microgrids project are reviewed at section 3:

- Demand & Renewable Production Forecasting
- Economic Scheduling
- Demand Side Management
- Security Assessment.

Additionally, the traditional direction of load flow at a given point on a distributor or interconnected network can be reversed by the output of a single integrated distributed generator. A number of generators that are connected in distribution systems and run at different times with different output power profiles, may result in different load flow patterns, so that overloading of components and voltages violating statutory limits may occur. However, matching of local generation to power demand may help reduce losses locally and could reduce losses overall. Thus, an analysis of energy balance is very important and precise results are required for the operation and control of Microgrids as . presented at sections 4.

2. Description of the Steady State Environment

In order to operate a MicroGrid in a coordinated manner it is important to provide a more or less decentralized decision making process in order to balance demand and supply coming both from the microsources and the MV distribution feeder. There are several levels of decentralization that can be possibly applied ranging from a fully decentralized approach to a hierarchical control.

2.1. Fully Decentralized Control

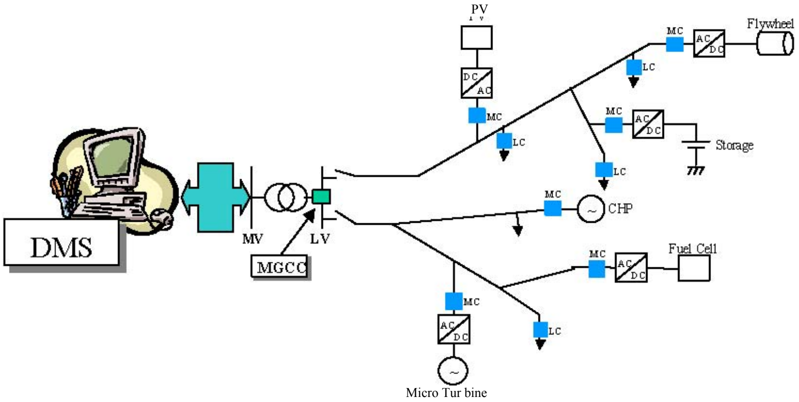
According to the fully decentralized approach, the main responsibility is given to the controllers of the microgenerators that compete to maximize their production in order to satisfy the demand and probably provide the maximum possible export to the grid taking into account current market prices. This approach is based on distributed multi-agent technology. The use of Multi Agent Systems (MAS) in controlling a MicroGrid solves a number of specific operational problems. First of all, microgenerators can have different owners, in which case several decisions should be taken locally, so centralized control is difficult. Furthermore, Microgrids operating in a market require that the actions of the controller of each unit participating in the market should have a certain degree of intelligence. Finally, the local DG units next to selling power to the network have also other tasks: producing heat for local installations, keeping the voltage locally at a certain level or providing a backup system for local critical loads in case of main system failure. These tasks suggest the importance of distributed control and autonomous operation. For the fully decentralized mode of operation the following remarks should be made.

. •There is no need to send a Schedule to the Distribution System Operator, since the only limits for taking or sending energy to the network are posed by the technical constraints of the installation.

. •In the Microgrid MAS there is only need for an extra supervisory Agent whose primary job is to record the bids of the Micro sources and the power flow. A transaction is valid only if it is registered in the supervisory agent and this is vital in order to avoid double offers to separate loads. In Market Operation its job is to create the final bill for each load or unit.

2.2. Hierarchical Control

In order to achieve the full benefits from the operation of microgrids, it is important that the integration of the micro sources into the LV grids, and their relation with the MV network upstream, will contribute to optimise the general operation of the system. For this purpose a hierarchical system control architecture comprising three critical control levels, as shown in Figure 1, was adopted in the MICROGRIDS project and a comparison with the fully decentralized control mode is presented as a result from the Task TB8 : Comparison of Centralized vs De-Centralized Control Strategies.



–Figure 1 Micro-Grid control architecture

- Local Micro Source Controllers (MC) and Load Controllers (LC)
- MicroGrid System Central Controller (MGCC)
- Distribution Management System (DMS).

The ***Micro Source Controller*** (MC) takes advantage of the power electronic interface of the micro source. It uses local information to control the voltage and the frequency of the microgrid in transient conditions. MCs follow the demands from the MGCC, when connected to the power grid, and have the autonomy to perform local optimization of the micro source active and reactive power production, and fast load tracking following an islanding situation. Local Micro *Load Controllers* (LC) are installed at the controllable loads to provide load control capabilities following demands from the MGCC, under a Demand Side Management (DSM) policy or for load shedding. A short review of the functions developed for this purpose are described in the following sub-sections.

The ***MicroGrid Central Controller*** **(MGCC)** is responsible for the maximization of the microgrid value and the optimization of its operation. It uses the market prices of electricity and probably DSM requests to determine the amount of power that the Microgrid should draw from the distribution system, optimizing the local production capabilities. It might use simple load forecasts (electric and possibly heat) and forecasts of power production capabilities. The defined optimized operating scenario is achieved by controlling the micro-sources and controllable loads in the Microgrid by sending control signals to the field. In this framework, non-critical, controllable loads can be shed, when necessary. Furthermore, it is necessary to monitor the actual active and reactive power of the components. These techniques can be considered equivalent to the secondary control of the interconnected grid.

Distribution Management Systems (DMS) deal with the management and control of distribution areas comprising several feeders including several MicroGrids. The traditional functions of DMS need to be enhanced with new features related to the operation of MicroGrids connected on the feeders and more generally to the operation with increased penetration of Distributed Resources.

3. Review of the control functions developed in Microgrids Project

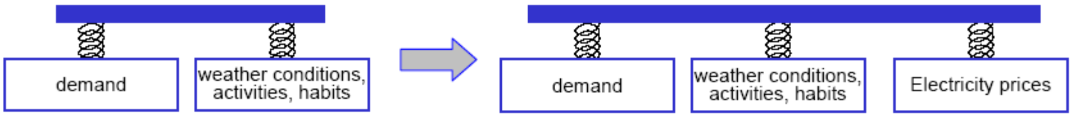
3.1. Demand & Renewable Production Forecasting

In the classical load-forecasting problem in interconnected or even autonomous power systems, demand depends on weather conditions, habits of the customers and activities. Due to these last two factors, it is highly correlated to the hour and type of the day or season of the year. Predictions are usually required for the next 24/48 hours with hourly or 30- minutes time steps. The forecasting accuracy is high, that is in the order of 1-5 % depending on the time horizon and the type/size of the system. Uncertainty can be estimated by classical methods, such as resampling. In fact, these forecasts can be provided with a high level of confidence. A large number of references and models exist for this type of load forecasting.

If someone wishes to downscale the problem to small power systems such as the systems of islands then very few results are reported in the literature with the main ones being produced in the Care and More-Care projects by Armines and RAL. In these cases it was concluded that although the variability of load starts to increase, the predictability remains at high levels compared to the classical case.

When however downscaling the demand prediction problem to the level of a microgrid, then situation is expected to change significantly. The aggregation or smoothing effect is reduced and uncertainty increases as the size of the microgrid gets smaller. On this difficulty one should add the increase in time resolution. We enter then the area of very short-term forecasting with reduced smoothing effects. Today there is a difficulty to find data from real cases to characterize adequately the problem. The shortest time resolution for load forecasting that could be efficient to implement could not be less than 10 minutes if one would like to speak about large-scale applications. This corresponds to load following type of functions. The load following patterns of individual customers are highly correlated with each other. Load following changes are often predictable (e.g., because of the weather dependence of many loads) and have similar day to- day patterns which can be captured with short term forecasting techniques.

In contrast to the classical load forecasting problem, it is expected also that the demand was correlated to electricity prices. Prediction models for demand may consider as input (predictions) of electricity prices to accommodate this correlation.



To date, load has not been able to respond to price because the communication and market systems did not exist. The market signals may be handled in the future over the internet. The local system operator would have a statistical understanding of the demand response, and would be able to forecast his load accurately. This capability is one of the key attributes for the distribution system of the future.

In the frame of microgrids project the generic adaptive fuzzy neural networks model is applied as a base-line advanced model. This option is an appropriate one for research purposes since it provides the flexibility to consider various input variables according to the availability of data.

3.2. Economic Scheduling

It is envisaged that the Microgrid can participate in the energy markets buying and selling energy to the grid. Moreover, loads may participate in the Microgrid energy micro-market bidding for their supply. In such a case a possible operation of the MGCC assuming that the MGCC acts as a market operator is described in figure 2.

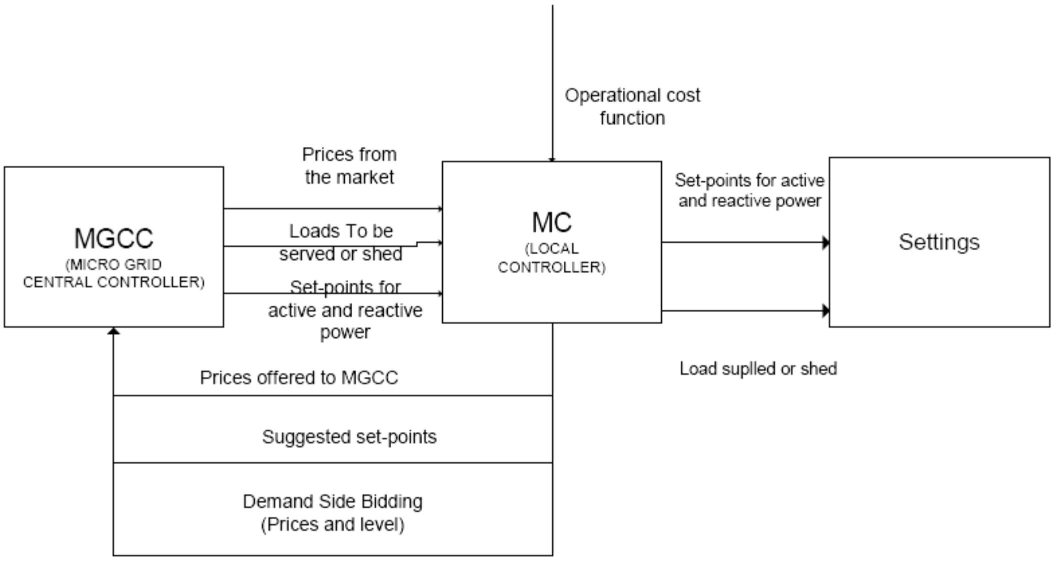


Figure 2 *Information flow between the MGCC and the Local Controllers*

The local controller MC takes into account the operational cost function of the micro-source and the prices of the market provided by the MGCC, in order to make offers to MGCC and provide the limits of production. These offers are made at 15 minutes interval for the next few hours, i.e. the optimization horizon.

The MGCC takes into account:

- The prices of the market
- The bids of the micro-sources.
- The suggested limits of production
- The demand side bidding for "low" and "high' priority loads

and solves an optimization problem according to the market policies decided to be followed in the specific Microgrid, Good Citizen or ideal citizen.

The MGCC, after the optimization process is complete, sends to the Local Controllers:

- The prices of the market for the optimization horizon at 15-minutes steps to prepare their bids
- The set-points for active and reactive power.
- The load to be shed or served according to Demand side bidding option followed.

The optimization functions consist of:

- Unit Commitment (UC) function, that determines which micro-sources will be committed at each time interval
- Economic Dispatch (ED) function, that decides the operating point (power) of each production unit (and load, if applicable).

The reason for applying both UC and ED is the fact that some units may have low variable cost, but high constant cost, For example, a unit may be expensive to start up, but once committed it might have lower variable cost than the rest committed units. Thus, it is more economical to operate at higher loading compared to the rest. In this case, an ED function is required to further optimize the economic operation of the Microgrid.

In the Microgrid studies the following techniques have been used up to now to solve the above problems.

- Priority list

- Sequential Quadratic Programming (SQP).
- Ant-colony optimization

In the following, the basic steps of the UC and ED functions are described:

UC function

1. Reads minimum and maximum capacity of the production units
2. Reads external market prices. The grid (external market) is considered as a "virtual", large generator with maximum capacity determined by the congestion limit of the interconnection. Therefore the units taking part in the market are number of micro-sources+1.
3. Creates priority list sorted according to the differential cost of each unit – ratio of cost in maximum capacity to maximum capacity of each one of the micro-sources.
4. The cheapest units are committed in market policy 1 until the demand plus an amount of spinning reserve are met and one of the units is the grid. In market policy 2 the selection of the units ends as soon as the grid is to be committed.

ED function

1. Reads minimum and maximum capacity of the production units.
2. Reads external market prices. As above, the external market is considered as a "virtual" generator with maximum capacity the congestion limit of the interconnection.
3. All committed units are dispatched at least at their technical minima.
4. The rest of the active demand, if the summation of the technical minima of the committed units is subtracted from the actual demand, is dispatched to the committed units, according to their bid prices, so that the active power demand is met.

3.2.1. Market Policies

The two market policies followed are briefly described

"Good Citizen": The Microgrid serves only its own consumers requesting zero reactive power from the grid

In this policy, the MGCC aims to satisfy the local energy demand using its local production, when financially beneficial, without exporting power to the upstream distribution grid trying to reduce the energy cost of the whole Microgrid. For the overall distribution system operation, such behavior is beneficial, because at the time of peak demand leading to high electricity prices, the Microgrid relieves possible network congestion by partly or fully supplying its energy needs. From the end-user point of view, the MGCC minimizes operational cost of the Microgrid, taking into account market prices, demand and DG bids. The owners of DG sources make profit from the difference between the bid price they suggest and the operating cost of their unit. The customers of the Microgrid share the benefits of reduced operational costs since they buy active power at lower prices compared to no Microgrid operation. These two aspects justify the use of the term "good citizen".

The following optimization problem is solved for each of 15 minutes interval and is a cost minimization problem subject to the technical constraints of each DG unit and the constraint of not selling energy to the grid.

Ideal Citizen: The Microgrid participates on the market by buying and selling active and reactive power from/to the grid

In this policy, the Microgrid participates in the energy market of the distribution area, buying and selling active and reactive power to the grid, probably via an Aggregator or similar Energy Service provider. According to this policy, the MGCC tries to maximize the corresponding revenues of the Aggregator, by exchanging power with the grid. The customers are charged for their active and reactive power consumption at market prices. The Microgrid behaves as a single generator capable of relieving possible network congestion, not only in the Microgrid itself, but also by exporting energy to nearby feeders of the distribution network. The owners of the DG sources make profit due to difference of the bid price and the operating cost of their own unit. The revenues of the Aggregator, are either the profit of the energy provider or, if the Aggregator is a co-operation of the end-users of the Microgrid, are distributed to those having shares of this co-operative structure. Since not only does the Microgrid try to avoid bothering network but also to relieve possible congestions in its neighborhood by providing power to the neighboring customers, this is equivalent to “ideal citizen” behavior.

The resolved problem is a maximization problem of the revenues, difference between income and expenses, with the only constraint of the capacity of the interconnection line to the grid.

3.3. Demand Side Management

The operation of microgrids opens new perspectives to demand side management. Significant part of the generation connected into microgrids is expected to come from renewable energy resources. The unpredictability of the renewable sources makes the islanded operation and dispatch of microgrids challenging. In this situation, the load control is very desirable and in some cases a real necessity. A common way to safely operate a small isolated microgrid where only renewable generation is available is to provide some storage, alternative generation and finally use distributed intelligent load controllers that shed loads in case of voltage and frequency excursions.

Two methods of Demand Side Management (DSM) have been developed within the MICROGRIDS project, the Shifting and Curtailment Management and the demand side bidding. Demand side management can also play a significant role on the liberalisation of electricity markets. If DSM system informs the microgrid central controller about the new load reschedule and the available load reduction capabilities for each time step of the next day, it could place bids in the market offering load reduction capacity.

3.3.1. Shifting and Curtailment Management

The load control system assumed in this case is centralized and the MGCC calculates suitable control actions and sends them to the loads. Based on the available information about the network, the loads and the DG sources, the central controller decides which load would be desirable to be consumed in the following time period. The criteria for deciding the optimal load consumption can vary widely from maximising either the use of renewable energy resources, or the economic benefit for the whole microgrid, or to minimize the amount of power imported from the main grid, peak reduction, and so on. The desirable load is usually calculated one day in advance. The central controller provides a curve: an objective load value for each time step (half an hour for example) of the next day.

The central controller calculates the aggregated amount of load that would be desirable to consume in the whole microgrid, or it could separate the network into different parts, using more complex algorithms that take network topology and loses into account and provide a different objective curve for each of the parts.

The demand side management system is not involved in the calculation of these objective load curves. The DSM system receives the objective load curves as an input and calculates the required load control actions in order to fulfill the desired load consumption. The system is flexible in the sense that it is completely independent from the criteria used to generate the objective load curve.

Moreover, the aim of the system that has been developed on this study is to build a general demand side management system capable of controlling most of the domestic devices and the commercial air conditioning at the same time. On the majority of the previous studies on direct load control, researchers focused on the control of a particular type of appliance, mainly water heaters or air conditioners. They came up with load control methodologies that considered in great detail the particularities of the device being controlled. The methodology developed within Microgrids controls many devices at the same time and the modeling of the behaviour of each

device is not, in general, so detailed in terms of considering thermal behaviours, these aspects are assumed to be locally managed by the next generation of advanced intelligent devices.
Two different load control algorithms have been developed under this concept. The first one-load shifting- delays loads from their expected connection instant to times that provide the smallest deviation between the objective load curve and the actual load consumption curve. The second algorithm curtails load. Load curtailment is something that should only be executed under exceptional circumstances for system security.

Load shifting

The algorithm runs a quadratic program and finds the best possible load scheduling. The payback of the devices that are moved is considered to be 1. The shifting algorithm is run periodically (usually on a daily basis). The developed shifting algorithm targets the domestic demand segment. It is based on the fact that, the consumption of some appliances can be deferred in time resulting on small disturbance to customer's comfort. Four shiftable appliance types have been identified: washing machines, dryers, dish-washers and storage water heaters. The control over these device types offers great control opportunities.

Load Curtailment

The curtailment algorithm is different and independent from the shifting algorithm. Curtailment control actions are not desired because they produce clear inconveniences to customers and therefore the algorithm is intended to run just occasionally in cases of possible system contingency. Drivers like maximization of the use of renewables or maximization of the economical profit within the microgrid hardly would bring a load to be tripped. In developed DSM system the load curtailment algorithm is run every time central controller requires. Central controller detects the need for load curtailment and sends a new objective load curve to the DSM system for a short time horizon. The load curtailment algorithm then calculates the required control actions that bring the actual load curve closest to the given objective load curve. The targeted devices by the curtailment algorithm are both domestic and commercial air conditioning units and electric central heating units. The idea is to make use of the thermal inertia offered by these devices and reduce their load consumption maintaining acceptable comfort levels. It is be assumed that the controllable devices have the capability to reduce their consumption a given amount of their nominal value by themselves acting over their duty cycle. Air conditioners are the devices that are mainly be targeted by the load curtailment algorithm.

3.3.2. Demand Side Bidding

The other approach in Demand Side Management is the Demand Side Bidding. Under this approach the participants of the microgrid state their willingness to have some loads not served at all by placing bids for this purpose instead of having MGCC intervene with the load control. The MGCC according to the bids of the customers decides on which load should be shed or not.
It is assumed that at least some of the customer loads are equipped with load controllers. Each consumer may have low and high priority loads and sends separate bids to the MGCC for each of them. In this way, the total consumption of the consumer is known in advance. Some of the loads will be served and others not, according to the bids of both the consumers and the micro-source producers. For the loads that the MGCC decides not to serve, a signal is sent to the load controllers in order to interrupt the power supply.
Two options are considered for the consumers' bids:
A) Consumers bid for supply of high and low priority loads
B) Consumers offer to shed low priority loads at fixed prices in the next operating periods.
In both options the MGCC:

1. Accepts bids from the consumers every hour corresponding to quarter of an hour intervals.
2. Informs each consumer about acceptance of his bids

3. Informs consumers about the prices of the external market. These prices help preparing the bids. For Microgrid operation as a good citizen, the market prices will be the highest prices, if security constraints are not considered.

In both options, if any load bids at prices higher than both the external market and the generators bidding prices, this load will be served paying at the Microgrid market clearing price as defined by the market policy followed within the Microgrid.

Option A

It is assumed that each consumer places bids for his own load in two levels and the prices of the bids reflect his interest for each load block. The "low" priority loads are the ones the consumer prefers not to operate when the market prices are high, and can be served later, when prices are lower (shift) or not served at all (curtailment). The MGCC knows the total volume of low and high priority loads and their price level and then decides which of them to serve and which not, based on the optimization function outcome. The MGCC aggregates the demand bids, the production bids and the external market prices and decides which bids will be accepted. The total demand of the Microgrid is the summation of the accepted demand bids making short-term load forecasting is less relevant. Information about the external market prices influences consumer bids, i.e. might shift load for a while in order to achieve lower costs for his electricity consumption.

Option B

In this case each consumer states the amount of load that can be shed in the next operating period. It is assumed that load can be shed in maximum two steps. The consumer will be compensated for his service, if his bid is accepted. In this option the MGCC has the right to shed "cheaper" loads, if they are on. Loads to be shed are considered as "negative" generation, if they are cheaper than actual generation, lowering the total demand. The MGCC takes into account the bids for shedding, the bids of production and either the aggregation of the total demand as the actual total demand to be met or a forecasted demand and accepts the demand shedding bids. The total demand finally to be met in the Microgrid is the actual demand minus the accepted demand shedding bids.

3.4. Security Assessment

For microgrid operation, dynamic security assessment provides a way to evaluate the robustness of the LV microgrid to survive to a sudden disconnection from the MV network. Such a sudden change on the system's operating conditions must be quickly and efficiently compensated by the microsources in order to avoid large frequency excursions, which may trigger the existing frequency relays, causing the system to collapse.

Since the microgrid dynamic behavior analysis is a complex and computational burden task, this evaluation is performed exploiting functional knowledge, generated off-line, and using machine learning techniques.

The generation of functional knowledge (learning set generation) requires the analysis of the dynamic behavior of the microsources operating together in the Low Voltage (LV) network under several different predetermined operating conditions, for the situation - passage to islanding operating mode i.e. disconnection from the upstream Medium Voltage (MV) network.

The degree of robustness of the system is evaluated by estimating the maximum frequency deviation the microgrid will experience following the considered disturbance.

In order to generate a representative learning set, a large number of dynamic simulations are required in order to generate a sufficient amount of data to cover the set of possible operation points (different scenarios of load and distributed generation) for the microgrid.

For each operating condition the security index – maximum deviation in frequency – is evaluated and kept. The dynamic simulations were performed using the simulation platform under the MatLab® Simulink® environment developed for the tasks in Work Package D of the Microgrid Project. In the deliverables of this workpackage the models of the microsources included in the simulation are describe. Only three-phase balanced operation of the network has been considered.

The main goal of this analysis is to evaluate and, if possible, to predict the preservation of a safe operating mode based on a determined set of conditions of the various microsources and loads in the LV network (different operating scenarios). This analysis will hopefully provide (in an operational time basis) valuable information about the robustness of the microgrid, allowing the central controller to define a more robust operation strategy to guarantee that, under a determined set of conditions, the moving from interconnected operation mode to islanding operation mode can be done safely – without large deviations in frequency.

The security index evaluation is performed through a Neural Network (NN), previously designed exploiting the information available in the learning set.

4. Review of energy balance methodology and Application in Microgrids

In order to reduce the influence of Microgrids on the electric power grid, supply and demand balance of Microgrids needs to be evaluated. Several studies have been conducted in energy balance modelling and different methods are analysed here. After this, the energy balance will be investigated in Microgrids by using available energy balance models. Next, the interaction of Microgrids with the energy supply system will be analysed, and the performance requirements of control systems will be studied.

4.1. Energy Balance Models

4.1.1. The energy balance model developed in Southampton University

Mathematical model

In [1], hourly energy balance was studied. The mathematical model of the energy balance of the Microgrid powered by several generators is shown in Equation 1.

$$D \leq \sum_{n} E_n \tag{1}$$

Where, D is the daily electricity demand. En is the energy produced by generator n. If the Microgrid utilizes PV generators and a single type of micro-CHP, Equation 1 then becomes as follows

$$D \leq (PSH)\sum P_{PV} + \frac{\eta_e}{\eta_h}\sum Q \tag{2}$$

Where PSH is the peak solar hours, ∑PPV represents the total size of the photovoltaic (PV) arrays in the Microgrid. ηe and ηh are efficiencies of micro-CHP to produce electricity and heat respectively, and ∑Q is the full heating load over all households with micro-CHP (combined heat and power) generators.

An example of hourly energy balance

Figure 3 gives the power generation profiles from micro-CHP and PV generators and a demand profile over typical days in winter. The power generation and demand profiles over typical days in summer are shown in Figure 4. The available electricity demand from former UK Electricity Association was employed, and average generation profiles by micro-CHP and the photovoltaic array were utilized. Figure 5 gives the cumulative energy balance during a typical cold winter day. Figure 5 indicates that energy storage of around 2.7 kWh would be required. Figure 6 shows the cumulative energy balance during a summer day. Almost identical needs for energy storage for winter and summer days were obtained in [1].

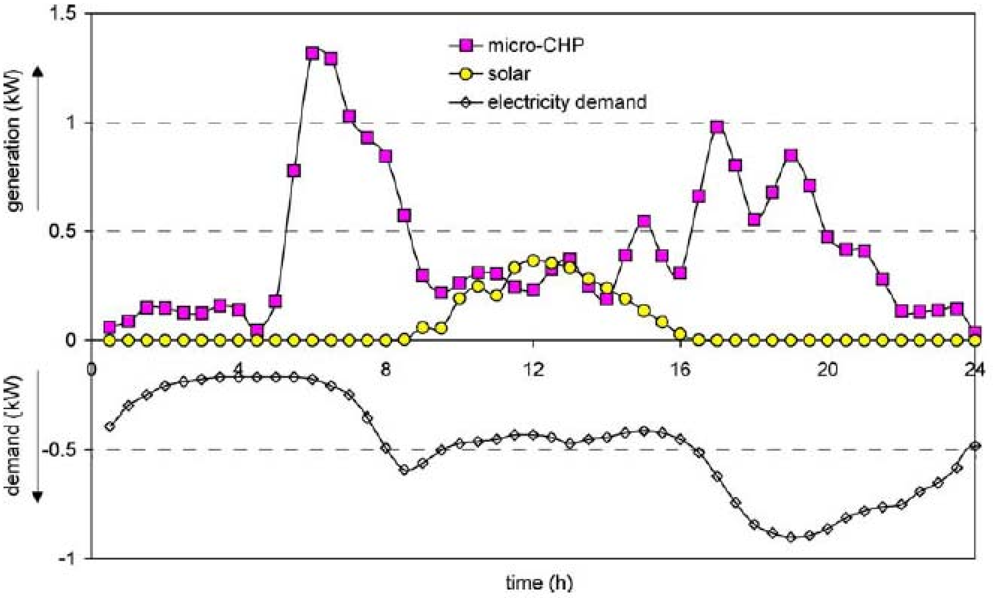


Figure 3 The daily generation and load profile during a typical winter day [1]

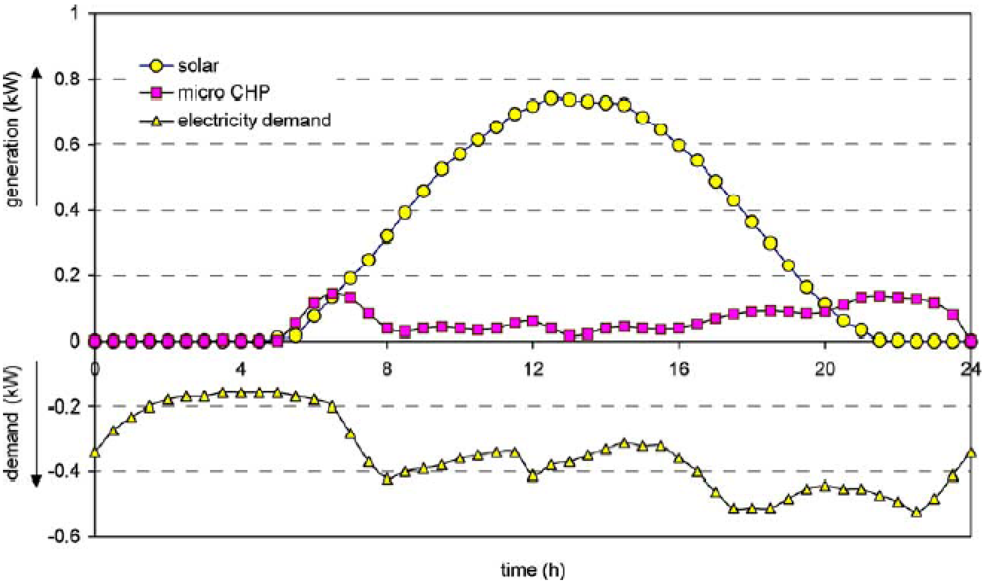


Figure 4The daily generation and load profile during a typical summer day [1]

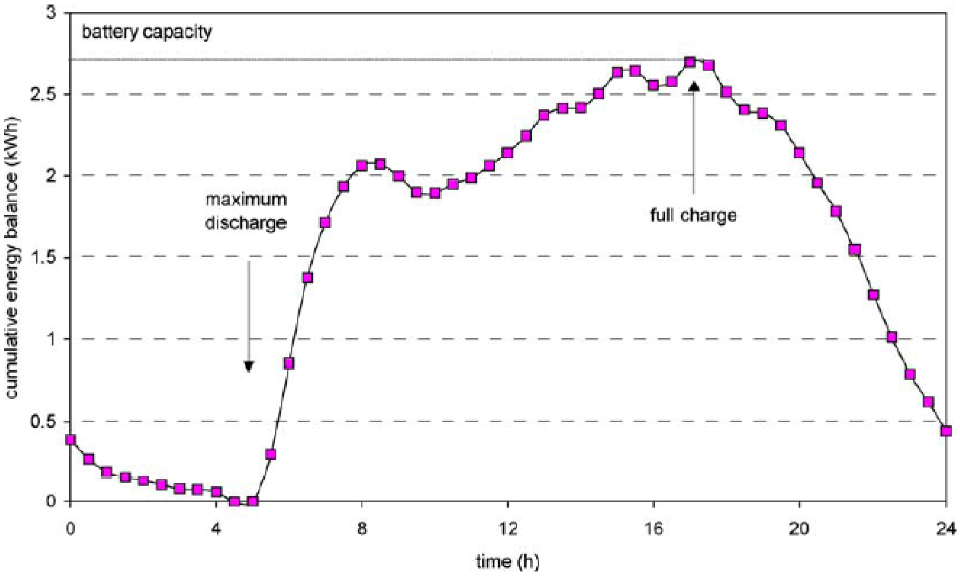


Figure 5 The cumulative energy balance per household during a typical winter day [1]

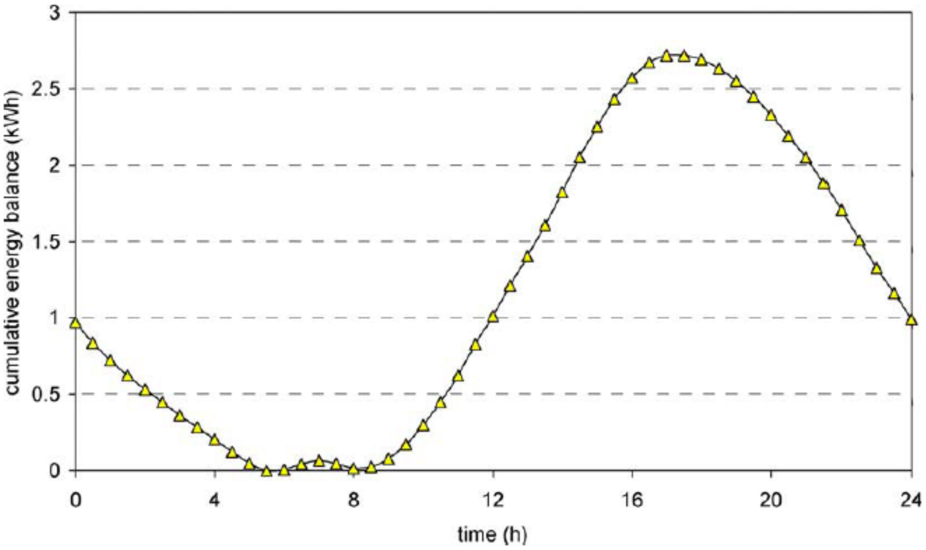


Figure 6 The cumulative energy balance per household during a typical summer day [1]

4.1.2. Energy flow model investigated by Geidl and Andersson [2]

The term energy hub is utilized in [2] to represent a part or a unit of a mixed energy carrier power system providing the basic features of different energy carriers, such as input and output, conversion and storage. Figure 7 gives an example of an energy hub transforming electricity, chemical, and thermal power. Based on the concept of the energy hub, the energy flow model was developed in [2], which is shown in Figure 8 represents line flows in the network, P indicates the hub input flows, and L is the load flows at the output ports. The mathematical model of the power balance in Fig. 6 can be described as Equation 3. D_{inm} is a coupling matrix, which can be obtained from the converter efficiencies and the hub-internal topology and power dispatch.

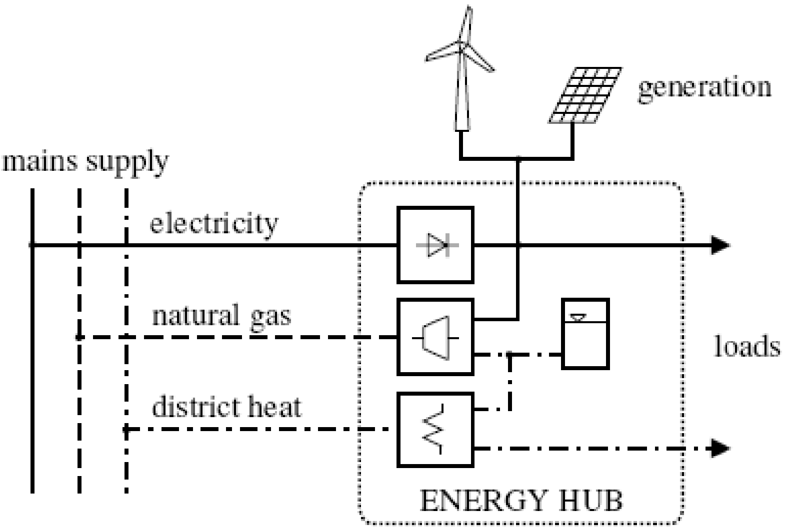


Figure 7Sketch of a hybrid energy hub with typical elements: power-electronic converter, micro turbine, heat exchanger, heat storage. Loads and smaller, distributed generation (e.g. small hydro, wind, solar) are connected to the hub [2].

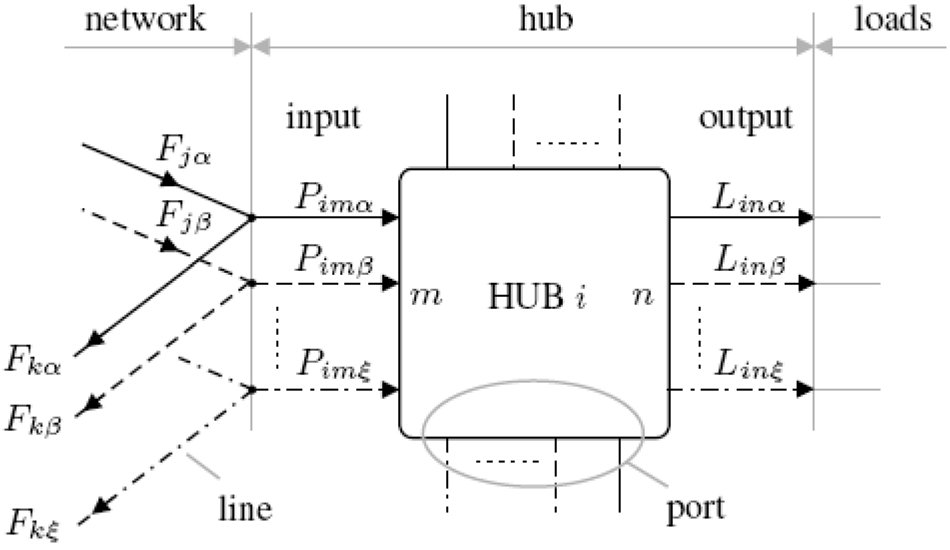


Figure 8 Model of an energy hub exchanging energy carriers α, β,…, ξ [2]

$$\underbrace{\begin{bmatrix} P_{im\alpha} \\ \cdot \\ \cdot \\ \cdot \\ P_{im\xi} \end{bmatrix}}_{\text{input } P_{im}} = \underbrace{\begin{bmatrix} d_{\alpha\alpha} & \cdots & d_{\xi\alpha} \\ \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot \\ \cdot & \cdot\ \cdot & \cdot \\ d_{\alpha\xi} & \cdots & d_{\xi\xi} \end{bmatrix}}_{D_{inm}} \underbrace{\begin{bmatrix} L_{in\alpha} \\ \cdot \\ \cdot \\ \cdot \\ L_{in\xi} \end{bmatrix}}_{\text{output } L_{in}} \qquad (3)$$

If storage is employed in the hub, the above Equation becomes:

$$P_{im} = \sum_{\substack{n=1 \\ n \neq m}}^{N} D_{inm} L_{in} + N_i \frac{\Delta E_i}{\Delta t} \tag{4}$$

In Equation (4), $\mathbf{N}_i$ contains the energy efficiencies of the storage devices including their network interfaces, for example power electronic converters. $\mathbf{E}_i$ is the stored energy.

4.1.3. The energy balance model studied by Jardan and Nagy

In [3], the system for converting solar energy to electric energy was illustrated in Figure 9. In the study, both photovoltaic cells and solar thermal panels were used to generate electricity. Besides the conventional function of PV generators, the solar thermal panels were used to generate heat, and then the heat was transformed to mechanical energy which was further converted to electricity.

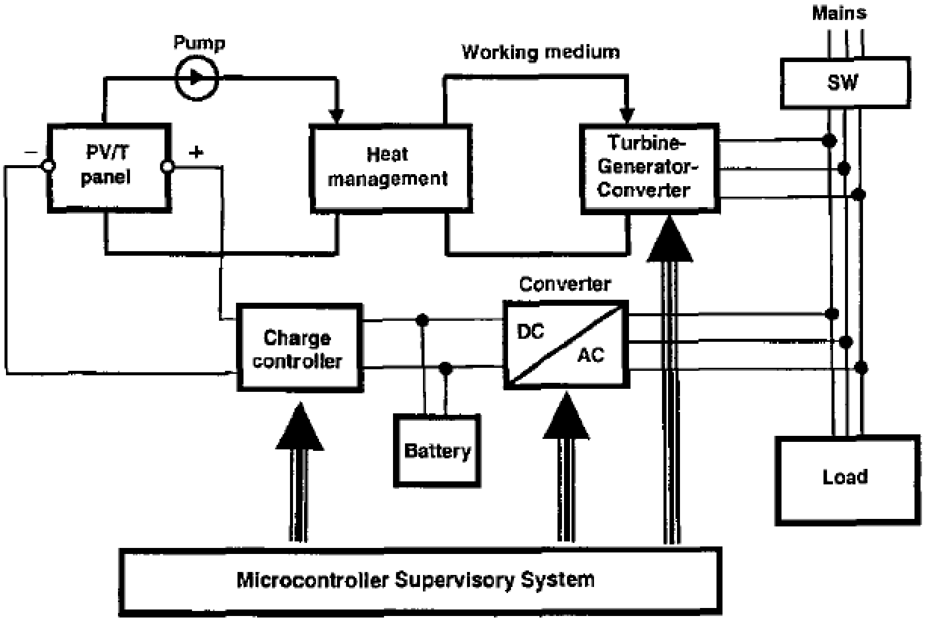


Figure 9 Block diagram of combined PV and thermal system [3]

Only the energy balance in the electrical energy conversion section of the system was simulated in the study using Matlab/Simulink, including PV panels, charge controller, battery, DC/AC converter. The simulink diagram is shown in Figure 10.

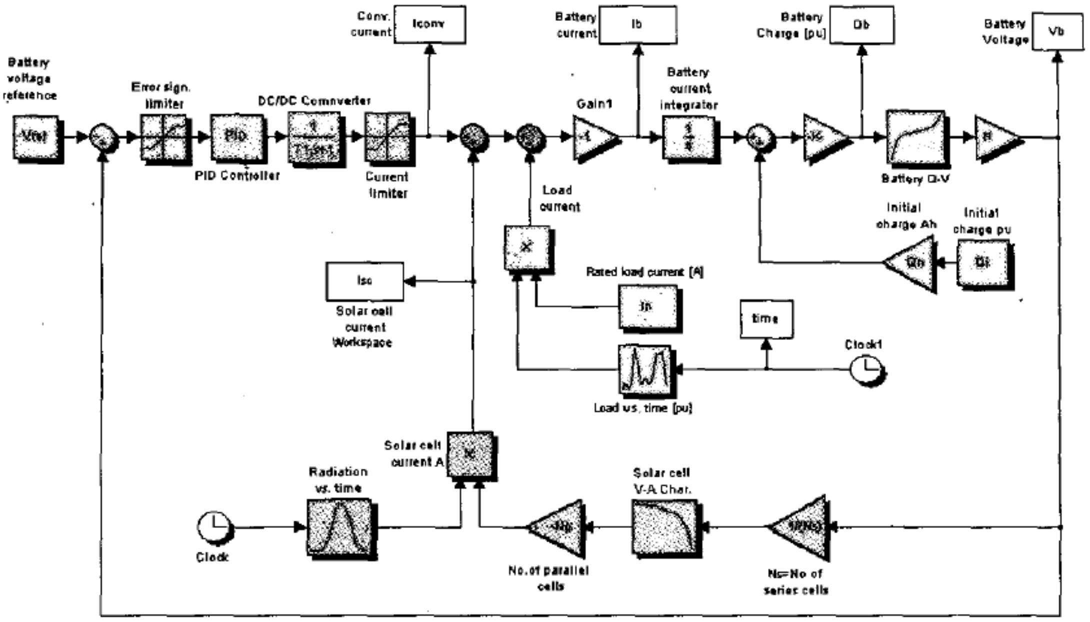


Figure 10 Diagram of Matlab/Simulink model [3]

4.1.4. Discussion on the energy models

Energy balance models have been developed and investigated for multiple objectives. The approach in [1] contains detailed analysis of the energy balance inside the Microgrid. The initial task of the energy balance in the micogrid powered by PV and micro-CHP is for sizing of the microgrid, and the hourly energy balance is for selection of the batteries.
The energy flow model developed by Geidl and Andersson contains electricity, heat and gas flows; conversion from gas to heat and electricity; storage. The purpose of the approach in [2] is to provide a tool for development of future power systems. An approximate model was investigated for depicting power flow and conversion of different energy carriers.

Jardan and Nagy only simulated the energy balance of the PV part of the PV-thermal energy system, including only conversion from solar energy to electric energy.

In this study, the energy flow model developed by Geidl and Andersson is used to analyse the energy balance of Microgrids including electric energy, heat and gas. The model of Geidl and Andersson is also employed to analyse interaction between a microgrid and the outside energy networks.

4.2. Investigation of energy balance within Microgrids

4.2.1. Models of components of Microgrids

1. Models of generators

(1). Photovoltaic generator
The generation of a photovoltaic generator is

$$P_{1ePV} = Area \times Irradiance \times Efficiency$$

(2). Micro-CHP generator

The CHP electricity generation depends on heat load, and this depends on the insulation of the building and how much heat is provided from other sources such as solar energy. The potential output of CHP depends on low temperature heat demands. The fraction of these demands might be met with available, cost-effective combustible fuels, or other source of high temperature heat.

Micro-CHP appliances will need to respond to the residence's energy requirements. These requirements may vary season to season or day to day. Micro-CHP appliances plus PV solar panels could potentially meet the changing electric and thermal demands. In order to make use of the natural source, output power of PV solar panel generators should be used fully. Control schemes incorporated into the system will enable micro-CHP to adjust its thermal and electrical output to best suit the homeowner's requirements. They will also need to be able to respond to residence's multi-energy requirements.

2. Models of loads

The domestic loads were estimated from the daily usage of a typical family dwelling, with the power demands from electrical appliances monitored over a 24 hour period.

There are obvious peaks in demand in the morning and early evening. The load will depend on the time of year and prevailing weather and light conditions. Different load profiles can be obtained for different family groups and usage patterns [1].

Fig 9 – Fig. 12 give examples of electrical and heat loads profiles of a semi-detached house of 3-person part-time afternoon working family in winter and summer. Fig 9 shows a daily electrical load profile of a 3-person afternoon working family during a typical winter day. Fig. 10 shows a daily heat load profile of a semi-detached house during a typical winter day. Fig 11 shows a daily electrical load profile of a 3-person afternoon working family in a typical summer day. Fig. 12 shows a daily heat load profile of a semi-detached house during a typical summer day [1].

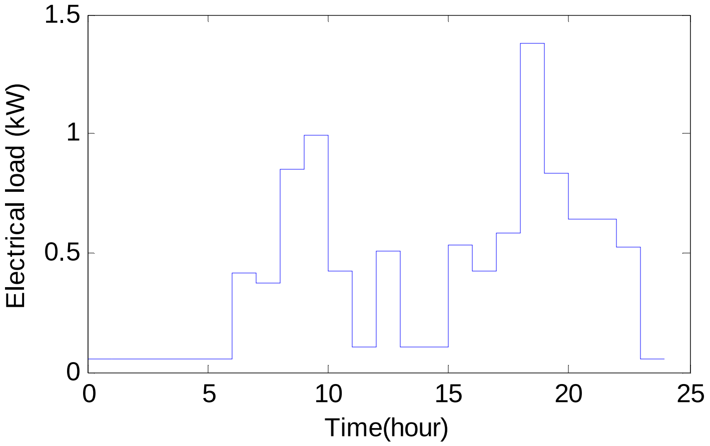


Fig. 9 Daily electrical load profile of a 3-person part-time afternoon working family during a typical winter day (after [1])

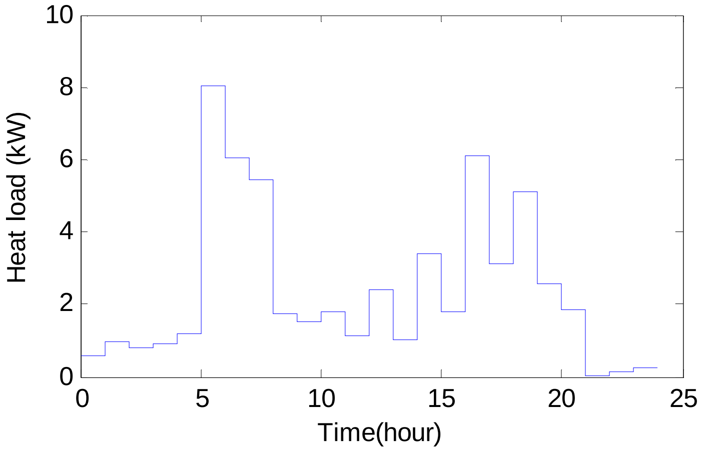


Fig. 10 Daily heat load profile of semi-detached house during a typical winter day (after [1])

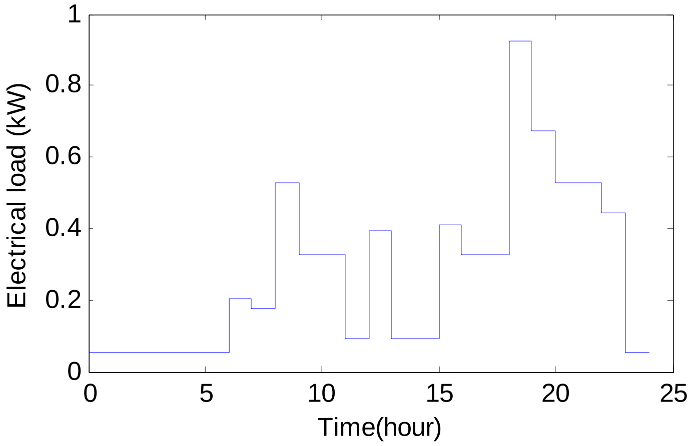


Fig. 11 Daily electrical load profile of a 3-person part-time afternoon working family during a typical summer day (after [1])

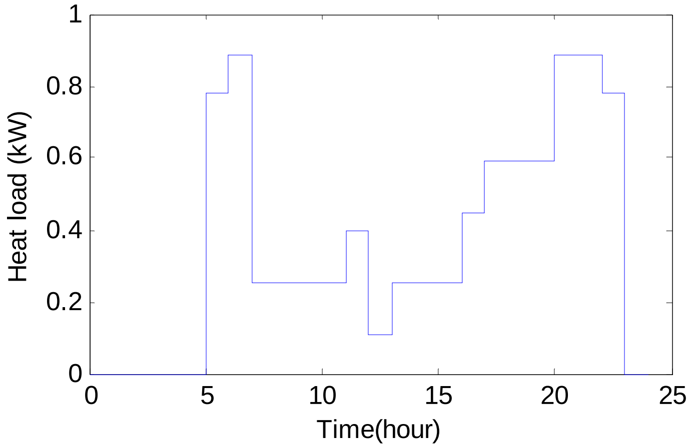


Fig. 12 Daily heat load profile of semi-detached house in a typical summer day (after [1])

4.2.2. Energy balance model

In the following discussion we consider a model of energy balance in a Microgrid of a domestic house, which includes a PV generator and a micro-CHP generator. The Microgrid has heat and electrical loads.

Suppose both electrical and thermal loads are not controlled. When the Microgrid is connected to the electrical network, the PV generator and the Micro-CHP generator maybe have base electrical loads and the network has the peak electrical load. The electrical grid is possibly used to balance peak electrical loads. When the microgrid is stand-alone, storage will possibly be required to balance demand and supply.

Fig. 10 shows the energy hub of the domestic house. The mathematical model of the energy balance is shown in Equation 6 and Equation 7.

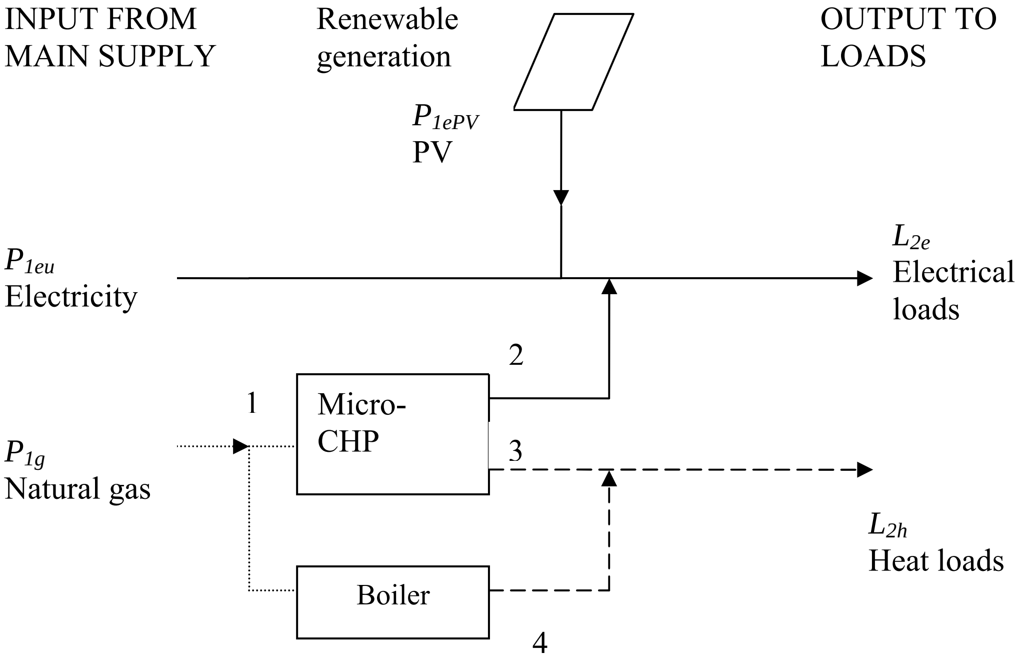


Fig. 23 Fig. 10 Energy balance of a domestic house

$$\underbrace{\begin{bmatrix} L_{2e} \\ L_{2h} \end{bmatrix}}_{L_2} = \underbrace{\begin{bmatrix} 1 & \eta_{12} \\ 0 & v\eta_{13} + (1-v)\eta_{14} \end{bmatrix}}_{C_{12}} \underbrace{\begin{bmatrix} P_{1e} \\ P_{1g} \end{bmatrix}}_{P_1} \tag{6}$$

$$P_{1e} = P_{1eu} + P_{1ePV} \tag{7}$$

Where,

η_{12} is the efficiency of transformation from gas to electricity of micro-CHP.
η_{13} is the efficiency of transformation from gas to heat of micro-CHP.
P_{1e} is the input electrical power from the utility and PV solar generators.
P_{1g} is the input gas power.
L_{2e} is the output electrical load.
L_{2h} is the output heat load.
v is a dispatch factor.
P_{1eu} is the input electrical power from the main electrical supply system.
P_{1PV} is the input power from the photovoltaic solar generator.

(1). The Microgrid is connected to the power grid

When the Microgrid is connected to the power grid, a micro-CHP maybe has the base thermal load. The boiler has the peak thermal load, and is adjusted to balance the peak thermal load. The PV generator and Micro-CHP generator maybe have the base electrical load. The electrical network has the peak electrical load, and is used to balance the peak electrical load.

(a). Simulation results in winter

Fig. 13 shows a daily heat load profile of a semi-detached house during a typical winter day. Fig. 14 gives a daily electrical load profile of a 3-person full-time working family in a typical winter day [1].

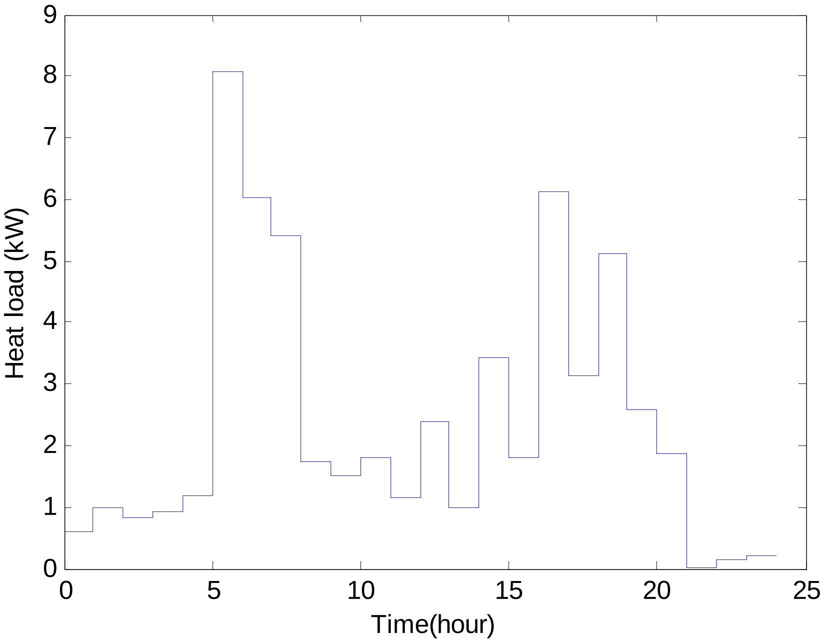


Fig. 13 Daily heat load profile for a semi-detached 3-person house in winter (after [1])

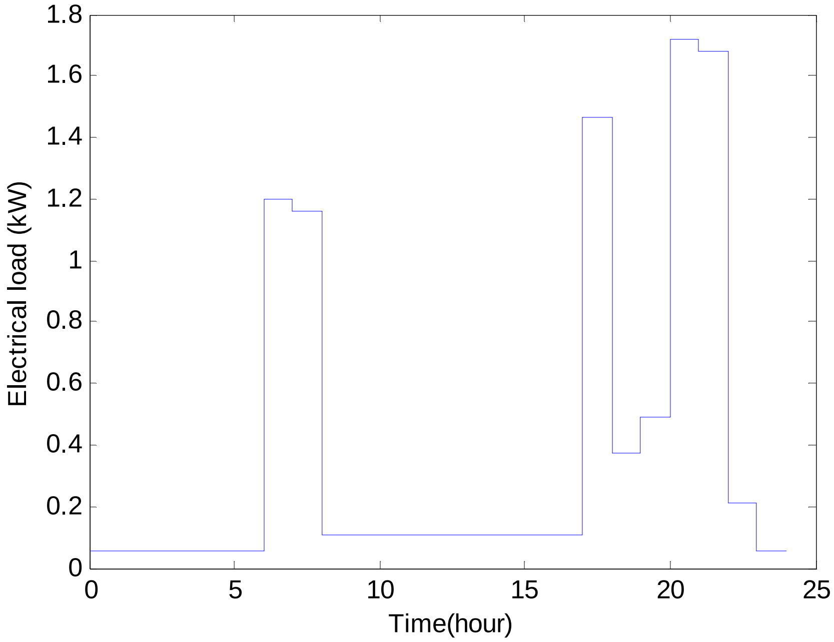


Fig. 14 Daily electrical load profile for a 3-person full-time working family in winter (after [1])

Fig. 15 - Fig. 17 give the simulation results by employing the energy balance model described in Equation 6 and 7. Fig. 15 shows daily solar energy input from PV solar panels in a typical winter day. Fig. 16 gives daily electrical energy from micro-CHP in a typical winter day. Fig. 17 shows daily electrical energy from grid in a typical winter day. Fig. 18 shows daily heat energy from micro-CHP in a typical winter day. Fig. 19 gives daily heat energy from boiler in a typical winter day. Fig. 20 shows daily input gas energy in a typical winter day.

The efficiencies of the micro-CHP in the figures are 30% to produce electricity and 40% to produce heat respectively. The rating power of the micro-CHP to produce electricity is 0.75 kW, and the rating power of the micro-CHP to produce heat is 1.0 kW.

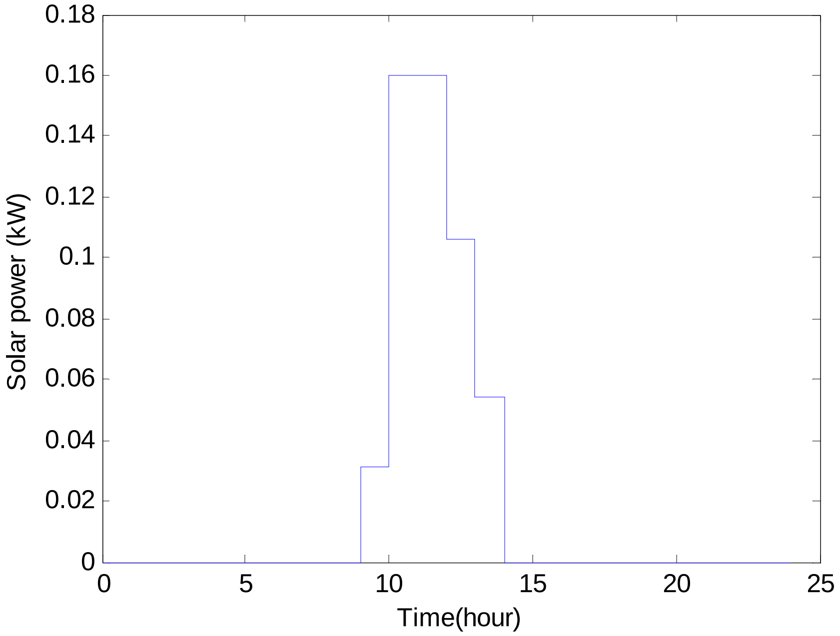


Fig. 15 Daily solar energy input from PV solar panels in a typical winter day

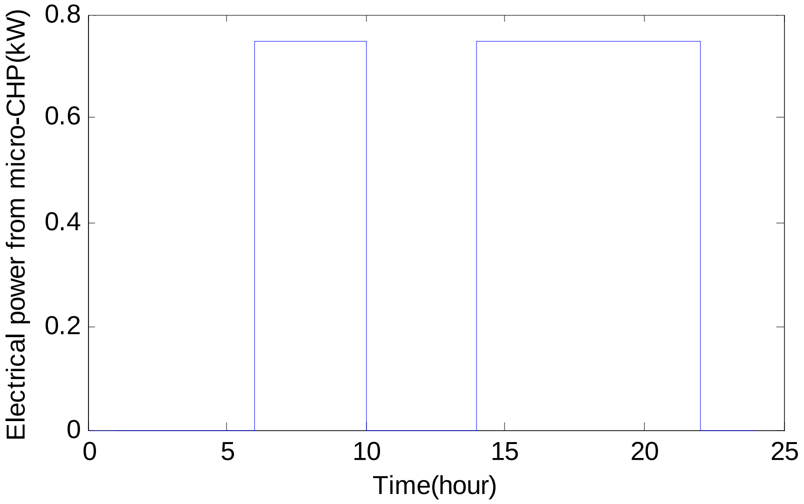


Fig. 16 Daily electrical energy from micro-CHP in a typical winter day

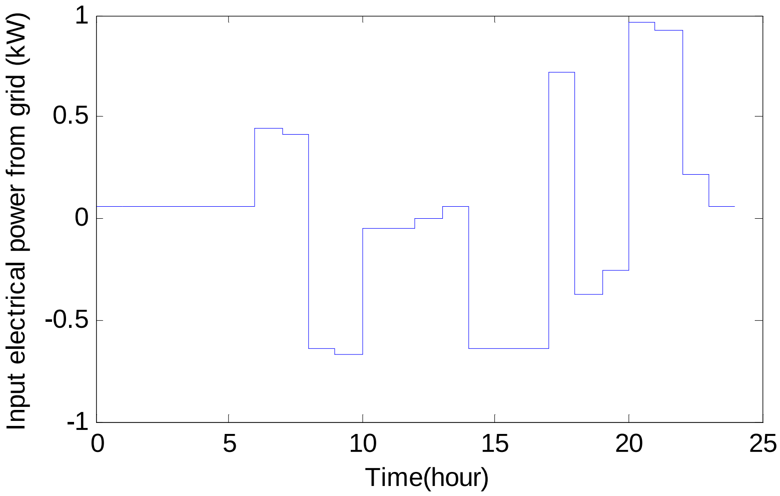


Fig. 17 Daily electrical energy input from the electrical power grid in a typical winter day

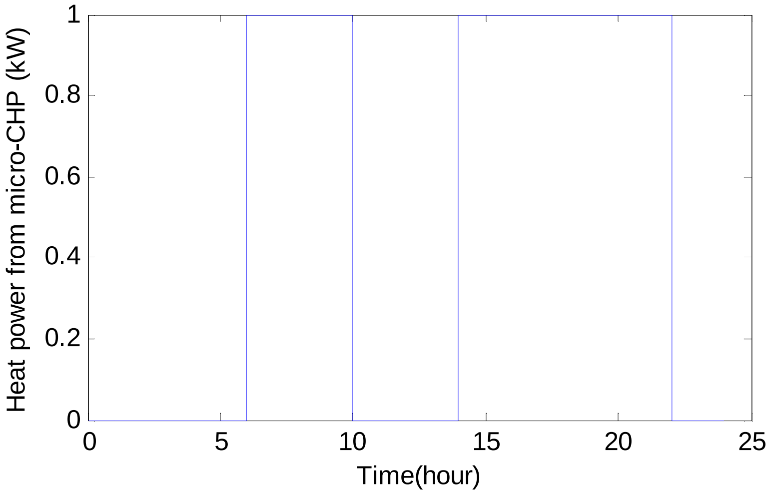


Fig. 18 Daily heat energy from micro-CHP in a typical winter day

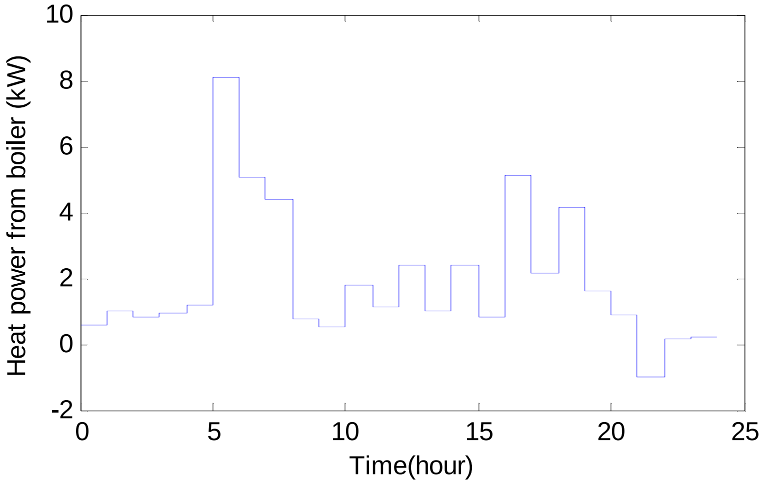


Fig. 19 Daily heat energy from the boiler in a typical winter day

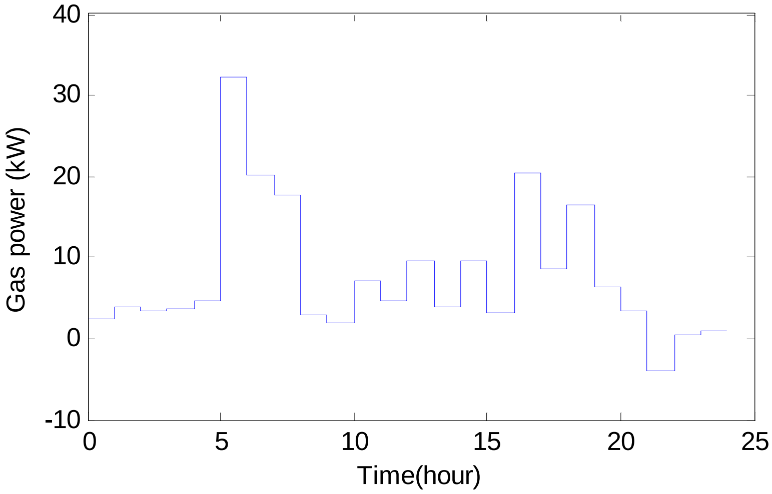


Fig. 20 Daily gas energy in a typical winter day

(b). Simulation results in summer

In summer, the Micro-CHP may be turned off. Fig. 21 shows a daily heat load profile for a semi-detached 3-person house in a typical summer day. Fig. 22 shows a daily electrical load profile for a 3-person full-time working family during a typical summer day [1].

Fig. 23 - Fig. 26 give the simulation results in summer by employing the energy balance model described in Equation 6 and 7. Fig. 23 shows daily solar energy input from PV solar panels in a typical summer day. Fig. 24 shows daily electrical energy from grid in a typical summer day. Fig. 25 gives daily heat energy from boiler in a typical summer day. Fig. 26 shows daily input gas energy in a typical summer day.

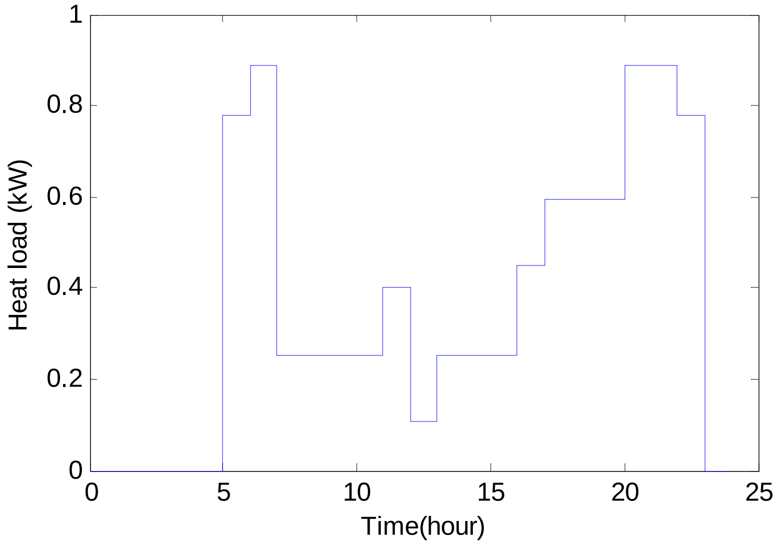


Fig. 21 Daily heat load profile for a semi-detached 3-person house in a typical summer day (after [1])

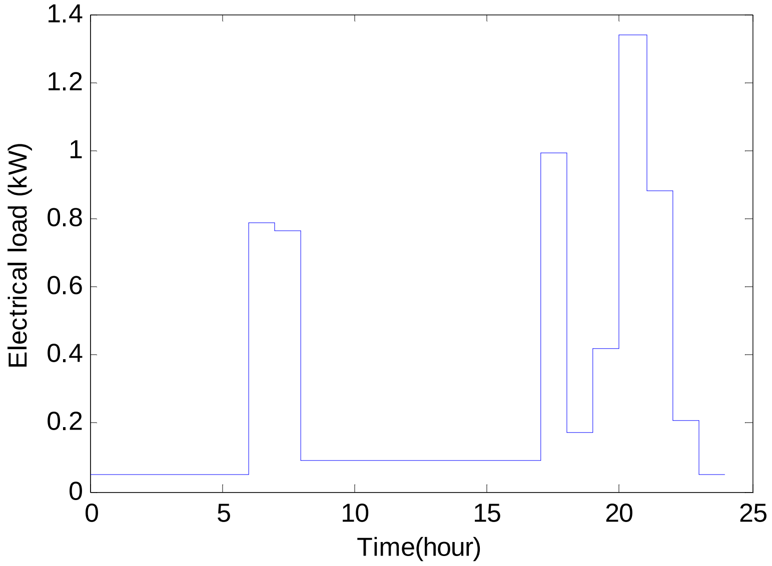


Fig. 22 Daily electrical load profile for a 3-person full-time working family during a typical summer day (after [1])

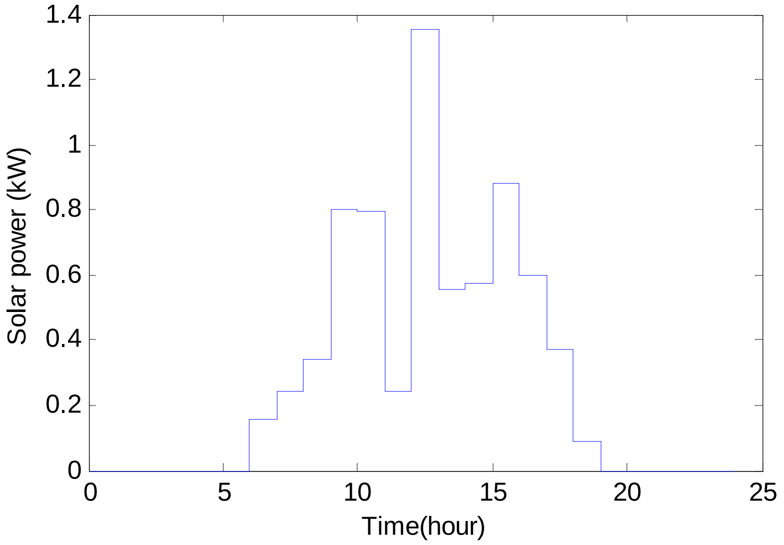


Fig. 23 Electrical power from PV generator during a typical summer day

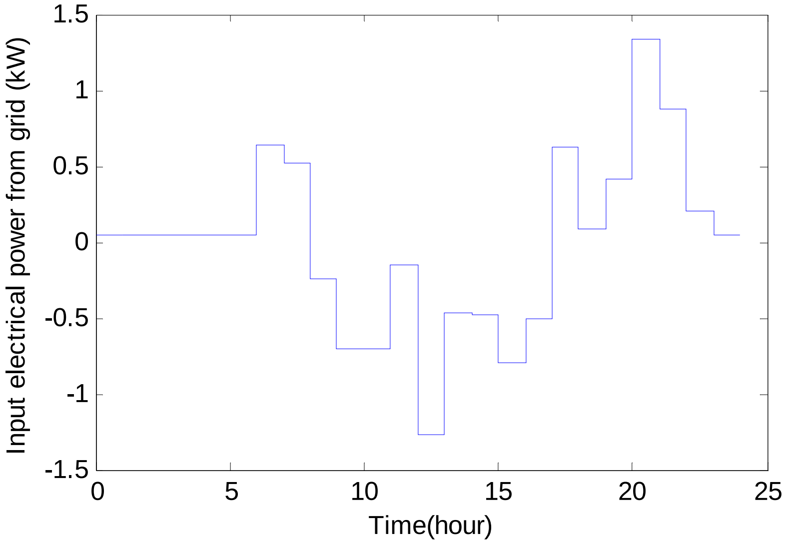


Fig. 24 Electrical power from utility in a typical summer day

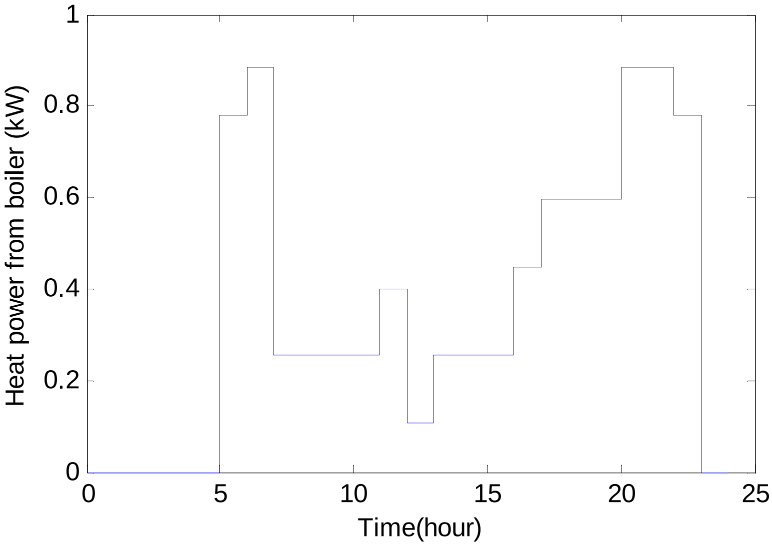


Fig. 25 Heat power from boiler during a typical summer day

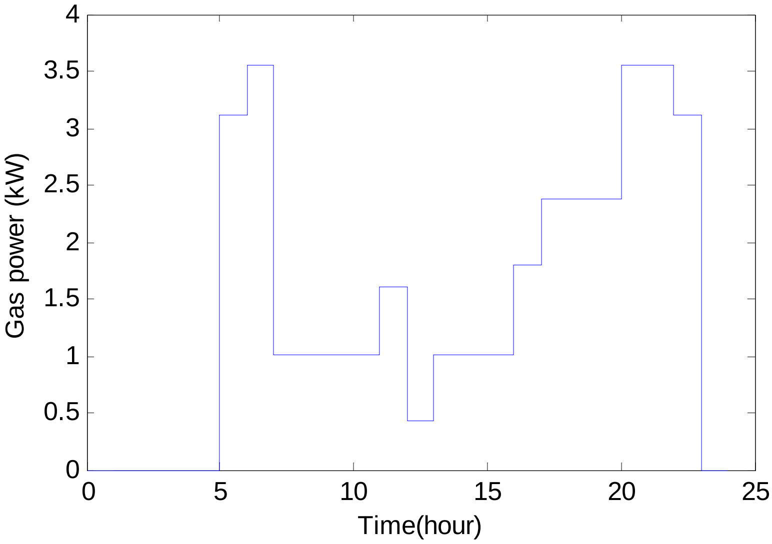


Fig. 26 Gas power in a typical summer day

(2). The Microgrid is stand alone

When a Microgrid is disconnected from the power system, the Micro-CHP maybe has the base thermal load. The boiler has the peak thermal load, and is adjusted to balance peak thermal load.

The PV generator has possibly the base electrical load. The Micro-CHP maybe has the peak electrical load, and is adjusted to balance the peak electrical load.

Electrical storage, possibly batteries are required for balancing the electrical energy in the Microgrid.

4.3. Interactions of Microgrids with the energy supply systems

The intention is that the Microgrids should be self-sufficient, but for security of supply and flexibility it would almost certainly be connected to the local electrical utility network, or even to adjacent Microgrids. These links may be bi-directional enabling the import or export of electricity, or, depending on commercial considerations, it might just be a unidirectional flow of power [1].

The connection of Microgrids to the electricity utility network can be either synchronous or asynchronous. The synchronous connection is performed through an electrical connection, a circuit breaker, and a transformer. The asynchronous connection is carried out by a direct current coupled controlled power converter.

In order to perform interaction between Microgrids, a central control level called Central Autonomous Management Controller may be required. A demand management system operates as an interface between the Microgrid and the outside energy network. Interaction between Microgrids and the regional and national electricity system may be managed by a set of markets.

In Andersson’s model, the interaction between Microgrids and the energy network is described as the energy flow from energy network to Microgrids, and from Microgrids to the energy network.

5. Requirements regarding the control

From the above analysis the following requirements have been identified for the control management and the energy balance management.

5.1. Demand Production Forecasting

The main outcome of the Demand Forecasting is that the variations in the Microgrid level demand are high and therefore any forecast has significant errors. These errors are unavoidable. The new modules of demand forecast should try to predict the limits of these errors by providing the proper coefficient. Furthermore, the modules should try to describe the load behavior.

5.2. Economic Scheduling

Two main proposals are suggested for the Economic Scheduling Functions:

The first proposal is to include in the market model the demand and renewable energy forecast variations. The modules should take for granted that especially the load has significant variations that affect the overall bidding process.

The second proposal includes the decentralized operation of the system. New algorithms should be included that provide decentralized operation of the system preserving the demand for optimal operation.

5.3. Security Assessment

The further development of the security assessment modules may focus in aspects.

The first issue is to include new disturbances and scenarios. The previous study focused in the frequency variation due to the disconnection of the main grid. The new algorithm should also study the voltage variation during the normal operation. A very interesting scenario is the overvoltage due to maximum production in time of low demand.

Another significant point is the practicality of the modules and more specific concerning the development and usage of such an algorithm in a real environment. Therefore an issue is whether an adaptive algorithm can be developed that is capable to identify possible insecure states by monitoring the rates of frequency or voltage changes during normal operation minimizing the requirements for off line simulations.

The final remark deals with the decentralized operation as well the multi Microgrid operations. The algorithm such take in to account the new operational scenarios and strategies. More specific in a decentralized environment the autonomy of the various units should be considered.

5.4. Energy balance control of Microgrids

5.4.1. Supply side management

In order to balance supply and demand energy of Microgrids, Ono et. al. used the accumulation deviation correction method. A power generation target is set using the short-term predictions and the neural network method [6]. Figure 11 gives the control diagram of the supply and demand balance. The power generation targets are set and sent to distributed resources on the basis of operation schedule corrected by the measurement, demand prediction and the amount of power generated by the grid in each control cycle. If *P(t)* represents the total generated electric power, and *D(t)* is the difference between the total electric power demand and purchased electric power from the electric power system in a regional system, the electric power deviation of power generation ΔP_T at evaluaton time T is given by the following equation

$$\Delta P_T = \int_T (D(t) - P(t))dt \text{ (kWh)} \tag{8}$$

Evaluation time T was divided into time sections, T_1 and T_2. The generation target set using T_2 is corrected using ΔP_{T1}. Therefore, the total generated electric power after the correction is

$$P^*(t) = P(t) + \alpha \cdot \Delta P_{T1} \text{(kW)} \tag{9}$$

Here, α is the coefficient to adjust the amount of the correction [6].

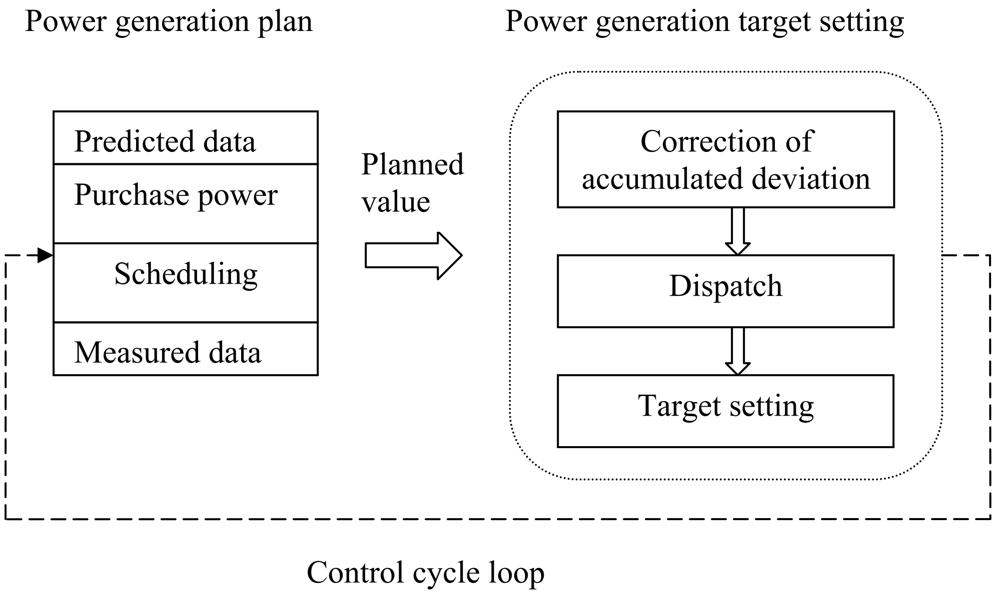
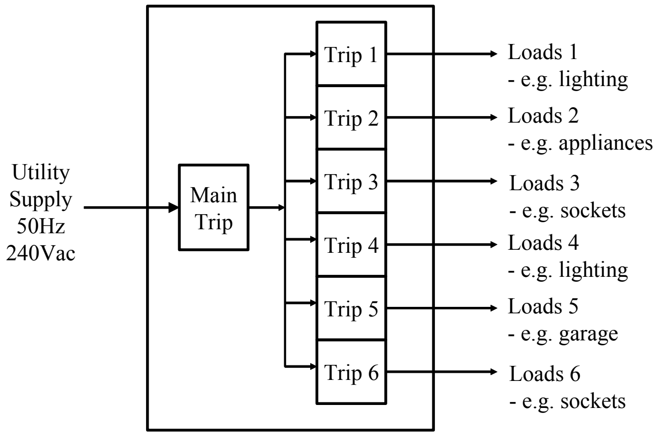


Figure 11 Flow of short-term balanced supply and demand control [6]

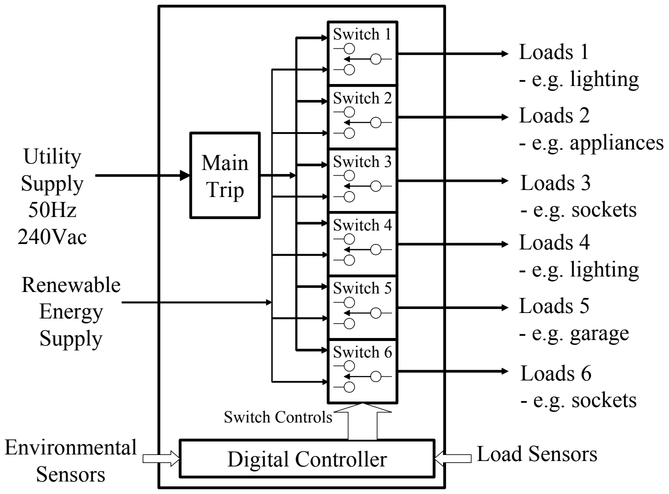
5.4.2. Load shedding [7]

In Microgrids, one of the biggest problems with connection to the public utility of renewable energy generators is the requirement to ensure adequate power quality, reliability and safety of that generator. Renewable generators should supply power to the load, and integrate directly with the utility. If a digitally controlled fuse-box is employed to substitute the simple fuse-box currently used, then some significant problems can be addressed with switches controlling the power to the load being from either the external utility or from an internally generated supply. Figure 12 shows the diagram of a digitally controlled fuse box. Here, power flow is unidirectional into the load.

A fuse box has the structure as follows:
An example of a typical domestic electrical fuse-box with a set of resetable trip switches and an overall trip switch is given below. Each load circuit has a nominal rating, and current flows are monitored. A digital controller knows and can predict the actual usage required. The controller has input from multiple sensors such as temperature, sunshine irradiance and wind speed, so the potential output can be predicted.



(a) Traditional fuse box



(b) Fuse box with the controller

Figure 12Diagram of a digitally controlled fuse box [7]

The control of the switches can be configured by programming into the fuse box the required operational characteristics. The controller monitors the energy generated by renewable sources and the load requirements. The controller send out commands to a number of the renewable generators if there is enough power to supply the loads.

The value of load profiles depends on time of day, season, weather and occupancy profiles. An accurate prediction of the likely load usage can be built up to maximize the efficiency of the fuse-box and also minimize the number of switching operations.

A comparison was made between the costs with and without the intelligent control of renewable energy sources. The resulting savings for a typical day were 20% when the fuse box control is used.

6. Reference

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