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An intelligent distributed system for flexible management of variable energy supply and demand in microgrids

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Część I

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Part I

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Chapter 1

Introduction

Over the recent years, a shift can be observed in the generation of energy production. For years, the production plants were entities positioned central in the grid, growing to meet increasing demands. This saw the change from coal and gas power plants to nuclear plants, but the essential architecture of the grid remained quite central and volatile: the grid depends on few powerful sources and interconnections. The shift came when renewable sources became capable of generating more power and this at an economically viable level. Production became dispersed over a larger number of sources within the grid. The relatively low cost of a low power renewable source (e.g. photovoltaic panels) and the fact that they became economically viable turned them into good investments for companies and even households. This further increased the shift by moving away from a strict consumer-producer network and adding entities that are both consumers and producers. The so called prosumer concept [122], an entity that not only purchases energy, but can also produce and export it to the power grid. This disperses energy production, making it less volatile, but adds new complications in energy management.

Traditional energy management systems mainly work under the assumption of unidirectional flow of energy: from the big production plants to the consumers. They fail to provide a well-suited solution to recent development involving prosumers. In the lower level of the grid, the energy flows from the distribution companies to the loads, located in the leaves of the distribution grid. Generation of energy inside the distributed grid ruins this assumption, as the energy flows bidirectionally. Thus, need for a new management systems appears [97]. This invoked the concept of microgrids: a microgrid can be treated as an aggregated prosumer, which consumes or produces energy. The aggregation of units into a microgrid has lowered the fluctuations than the individual units and such prosumer-like sub-networks can be mainly energy self-sufficient and may work in a so-called island operation mode, but periodically they may buy or sell energy from or to the higher level grid (distribution network). Just as power needs to be balanced in the main grid, the sub-networks also need their own power balancing system: their efficiency increases when they are less dependent on the external network and this calls for good power management.

A microgrid can have multiple generators, from photovoltaic panels and wind turbines to gas microturbines. As these generators are dispersed in the grid, the idea of a decentralized management system arises as a natural solution. The fact that the microgrid deals with lower voltages makes such an approach more feasible. Recently, decentralization of decision making in computer networks is realized more and more often by multi-agent systems [99]. The paradigm of the multi-agent approach for energy management is the core topic of this work. Agents are concepts that can represent a real world object or an abstract concept. The aim of the agents can differ, but usually involves either individual or global optimization. In the power management problem, agents can be associated with devices, like power sources, loads, and energy storages. They have their own knowledge and individual goals defined: some power sources should be given priority in specific conditions, other conditions can require some loads to activate or deactivate. The behavior of the agents has to be defined to achieve these goals. Agents communicate with others in order to ensure security of the energy supply, and to reduce (minimize) unplanned shortages or surpluses. Thus, both sides, the supply and the load devices, take part in resolving imbalances of the energy. This forms a distributed energy management system.

In this work, a multi-agent system was developed to test the possibilities of balancing in short time intervals. The main argument to pursue a multi-agent based approach - apart from the decentralized architecture - is its modularity. There is no need for a central entity. When a new device gets added to the grid, it suffices to have agents properly defined for the new device, but no changes are required to the rest of the system. This results in a very robust system, where the removal or addition of devices is automatically caught and introduction of new devices (e.g. a new power source or power storage unit) does not require any modification to the balancing system.

A multi-agent system is a paradigm that suffers from similar drawbacks to paradigms in artificial intelligence. The system should work autonomously, based on the behaviors implemented. Such systems are very powerful but are difficult to develop: if the system does not behave as expected, it is not always easy to find which behavior in the implementation is the culprit and where the system should be modified. As such, the development of such a system requires a lot of testing and verification. To this purpose, in this work, attention also went to simulating devices present in a microgrid. This involves not only simulation of the sources (photovoltaic panels are dependent on irradiance, wind turbines on wind), but also simulation of user behavior, people using appliances or devices. To this purpose, the case of a planned research institute of "The Conversion of Energy and Renewables" in Jabłonna was used, as this provided an environment were realistic simulations of people's behavior can be envisioned.

The main goal of the multi-agent balancing system is to balance energy, but this has additional constraints: ideally, the use of renewable sources should be maximized, and the cost of the operation of the microgrid minimized. The agents need a mechanism to communicate this, and for this the concept of prices and auction was used. An auction is a well-suited solution to solve the problem where decentralized, autonomous parties tend to realize only their own goals. As in the actual trading, particular entities can reach sub-optimal allocation of the goods in the competitive environment, even without the assumption of the shared knowledge. Thus, in the Agent-based Short-time Power Balancing System for the microgrids, the bargaining of the unbalanced energy is performed in a way that minimizes differences between actual energy production and consumption. To suppress imbalances, the reaction time should be as short as possible. Several type of auctions exist in literature, here a quick auction type was necessary and the one-side first-price sealed-bid auction has been chosen. Another objective in this work is to verify and discuss the application of this particular auction algorithm and to present results of its implementation in a simulated microgrid.

In this work, the applicability of a multi-agent system for short term power balancing is considered. This involves mainly the development of a framework in which simulations can be run, along with a necessary study on how the different devices in the grid behave and how they can be simulated. Studying the feasibility of the agent system is an important step, as the modularity of the agent system lends itself for additional extensions, prediction of future behaviour is one aspect that might allow a microgrid to behave even more optimal. Such extensions are interesting, but cannot be developed with a proper working management system in place.

The outline of the thesis is as follows. In the chapter 2 the basic information about the microgrids, their evolution and the technologies that helped its development are presented.

The problem of power balancing is presented and the balancing with different level of information accessibility is discussed.

Next chapter describes the power management system that was giving the context and environment for the multi-agent system of Short-time Balancing that is the core of this thesis. Description of the subsystems is presented: model of the grid, the long-term planing system, subsystems for energy trading and reliability factor calculators. This chapter also describes the simulators of environment for testing purpose. Supply generator introduces a novel usage field for matched-block bootstrap and power consumption generator is an attempt to simulate human behavior.

The chapter 4 presents the theory of agent approach. The definition of agent is discussed as there is no common agreement over formal definition. Agent framework used in implementation of system is described.

Chapter 5 is presenting the multi-agent system realizing the short-time power balancing. The architecture of the system is presented as well as algorithms of agent operation and the structure of their behavior.

Following chapter presented the experiments and testing of the developed system. Final chapter concludes the thesis.

Chapter 3

Intelligent distributed system for flexible management of power

3.1 Introduction

The idea behind this thesis, using a multiagent system for power balancing, emerged as part of work for grant N N519 5802 38 financed by the Polish Ministry of Science and Higher Education. The project was aimed at creating a model of a microgrid and an intelligent distributed system that manages energy on all stages. Several groups were involved in the project, including the author of this thesis who implemented the short-time balancing module. The project concluded in November 2013.

The aim of that project was very practical: Polish Academy of Sciences was set to start building a science and conference center that specializes in research on renewable energies and energy conversion, and a model to manage the energy in this building was necessary. Construction started in December 2013 [128]; the official name of the project is Research Centre of the Polish Academy of Sciences, "The Conversion of Energy and Renewables" in Jabłonna. The research used plans and projects from 2010, which are not identical to the current plans. This is due to consultations and modifications to the real plans. However, the research is considered to be broader than the research center and should be general and configurable for different microgrids. For this purpose, additional devices were kept in the model (e.g. a water turbine as a controllable power source with changeable upper production limit, which currently is not part of the research center). The description of the hardware and layout is still based on the old plans, as finalized specifications were needed to perform the research. The methods developed in the research are general, which allows for using hardware with different specifications.

The energy in this research was understood in broader sense: heat, cooling and electrical energy. The main source of heat are condensing gas boilers (CGB), installed in four of the buildings. Electricity and heating are interdependent: air-conditioning and ventilation use power to operate and impact temperature, while on the other hand a reciprocating engine and a gas microturbine are combined heat and power (CHP) units, the heat from exhaust is recuperated and used for heating. Temperature change and water heating is much slower process than the flow of electricity. Heating management is simpler and well recognized; consequently this theses focuses solely on electrical energy.

The microgrid used in the research is based on the original plans for the research center and is described in detail in 3.2. The energy will be managed by an intelligent distributed system, called an energy management system (EMS). The system is made to be flexible, allowing for easier adding and removal of devices, which will be achieved by a multi agent system. The components of the energy management system are elaborated upon in 3.3. As the research was performed without any existing hardware, it was necessary to simulate hardware for generators, energy storage and consumers. This is more tricky than it seems, as renewable sources are dependent on weather conditions (sun, wind, etc.) and the usage of man-controlled devices shows random behavior. Consequently, it was necessary to create appropriate tools to simulate a fully operational microgrid of the proposed layout; the approach for this is described in 3.4.

3.2 Modelled microgrid

3.2.1 Description of the microgrid

The models of the grid and devices were designed by a group from Warsaw University of Technology, schema of the network and description of microgrid can be found in: [125] and [92]. The group made a realistic plan of the microgrid and considered all technical and economical aspects of such grids in Polish conditions considering polish energy law [113] and current research works such as integration of distributed energy resources [51], AC-coupled hybrid systems [19] and island mode operation [102].

The scenario considers a microgrid near the Warsaw area (central Poland), constructed as a complex of 5 buildings [125]:

- Laboratory of Solar Techniques (LST) – the building has 975 square meters of surface area, distributed over two floors, and houses a laboratory hall with high ceiling, laboratories, seminar halls, workshops, boiler room, distribution board, ventilation facility, lodge, utility rooms, toilets and corridors;

- Laboratory of MicroCHP and Ecological Boilers + Laboratory of Wind Power Engineering (both in one building LMEB+ LWPE) – a two floor building with a usable surface area of 874 square metres, containing a laboratory hall, laboratories, seminar rooms, workshops, boiler room, distribution board, ventilation facility, lodge, utility rooms, toilets and corridors;

- Laboratory of Energy Consumption Rationalization (LECR) – the biggest building, estimated size around 5010 square meters, comprising conference hall, laboratories, workshops and seminar rooms, social rooms, recreation areas, reception, laboratories, offices, administration rooms, restaurant, cafe, technical rooms, utility rooms, ventilation facility, boiler room, distribution board, toilets, halls, corridors and a hotel, with 16 1-person rooms and 16 2-person rooms;

- Laboratory of Power Industry Safety Engineering (located in two buildings LPISE1 and LPISE2) – their combined usable surface would be around 2100 square metres.

The microgrid is a low voltage network (LV, 0,4 kV), connected to a medium voltage supply line (MV, 15 kV) via an MV/LV (15/0,4 kV) transformer substation. The distributed generation sources that are considered are: photovoltaic panels (PV) (50 and 60 panels of 210 W rated power each), micro wind turbines (MWT) (3x10kW), a micro hydroelectric power plant (MHPP) (3 turbines, 90W each), a gas micro combined heat and power (CHP) units: gas microturbine (GM) (65 kW) and reciprocating engine (RE) (50kW). Additionally, the microgrid is equipped with the power storage units: a set of accumulator batteries (whose capacity is 50 kW) and set of flywheels (their capacity is limited by the electroenergetic transformers to 50 kW). The simplified diagram of the microgrid electrical installation can be found in [125]. The report [90] describes the details of the power network of the microgrid, this report was accompanied by the detailed technical pictures of the grid layout (given in the Appendix) – these were used to create the usage simulator (described in section 3.4.3). A sample diagram of the grid layout is presented in Fig. 3.1.

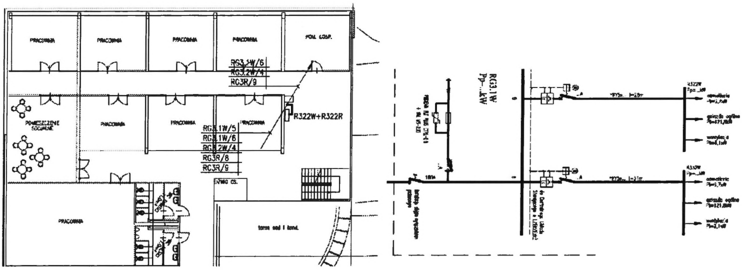


Figure 3.1: Sample description of the part of microgrid.

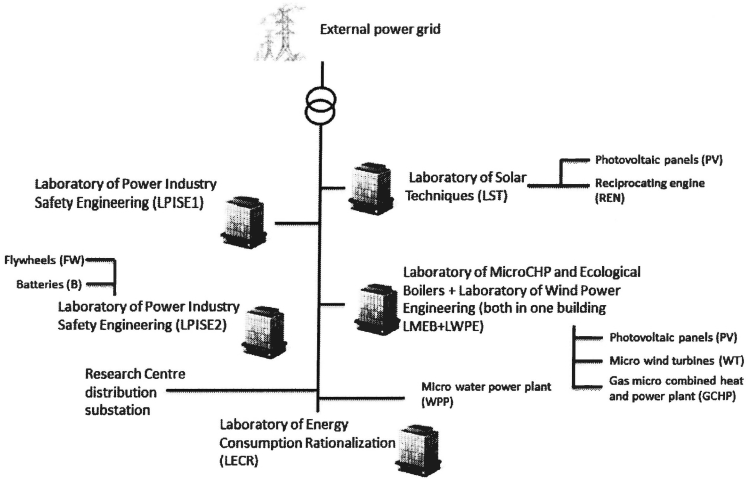


Figure 3.2: Sample description of the part of microgrid.

The network is divided into two sections: the unconditional supplying section, and the conditional supplying. Connected to the unconditional supplying are all equipments that have to have priority of receiving power, such as e.g. controllers of sources and power network, important computer equipment and emergency lights. The conditional supply connects those devices that can be switched off in the event of power deficit. In [125], authors suggest that the unconditional supplying section should be outside of the control of energy management system (EMS). In this work, all nodes, including unconditional supply, are known and considered by the EMS. While it does not directly control their usage of power but rather schedules events, knowledge on the unconditional supply may prove useful for proper scheduling.

The energy consumption units (loads) were divided into following categories:

- the laboratory equipment (conditionally reserved)
- the technological kitchen equipment (conditionally reserved)
- the heat pump (conditionally reserved)
- the heating control equipment (unconditionally reserved)
- the ventilation and cooling system (conditionally reserved)
- the lighting system (both unconditionally and conditionally reserved, depending on the purpose)
- the electrical sockets for general use (conditionally reserved)
- the electrical sockets for a computer hardware (both unconditionally and conditionally reserved, depending on the purpose)
- the electrical equipment in the hotel rooms (conditionally reserved)
- the electrical equipment in the conference rooms (conditionally reserved)
- the lifts (unconditionally reserved)

In case of the lighting system and electrical sockets for a computer hardware, the type of reserved connection depends on the location and purpose of the equipment: emergency lights are connected to the unconditionally reserved power lines, whereas the other lights in the rooms are connected to conditionally reserved power.

A node of the grid is a point to which devices are connected, the node groups similar types of devices, e.g. lights, computers, etc. From the grid point of view the node is the smallest unit that is measured and controlled. The number of devices that are connected to single node varies: some nodes can gather a large number of small devices (lights in the conference room), some have a single device connected (specialized nodes, e.g. node R211.1W is specially used for research of microturbines and gas turbines).

Control over the devices by the computer system is limited. Some nodes contain controllable devices – such devices can adjust their operation point. In this case, the computer system can request to adjust produced or consumed power accordingly, within the technical limitation of the device. Such devices are most non-renewable power sources (reciprocating engine, gas microturbine), water turbine, battery, etc. Wind turbines and photovoltaic panels are considered uncontrollable devices as the amount of their production depends on the weather conditions and cannot be changed by computer system. Larger renewable sources are equipped with controllers, and they can be under control of an EMS, but the models of energy sources considered in this project can only maximize their production in given weather conditions.

As mentioned before, island mode operation of a microgrid is a situation when the microgrid is disconnected from the external power grid, making it unavailable to provide or take large quantities of power to/from the microgrid. Switching to and operating in island mode is a challenge for the control system. The supply and demand have to be balanced at any point in time. The control system has to choose the nodes that will be disconnected and perform their safe switching off. Due to the small power production capabilities in the considered microgrid the operation control in island mode is limited to one single procedure. This procedure consists of switching on the reciprocating engine and disconnecting all conditionally reserved nodes. The engine will synchronize the phase of the power in the microgrid. If, after switching on all available power sources there is sufficient power, small imbalances are dealt with. In the event of deficit of power, not much can be done and some devices would not have sufficient power to operate. A better solution would be to assign priorities to the devices use techniques of Demand Side Management (DSM).

The simplified schema of the microgrid is presented in Fig. 3.2. This shows the buildings of the microgrid and the power sources connected to each of them, example of the node is presented to give the idea about the level of control. All together there are 128 nodes, from which 54 are unconditionally reserved. In appendix 7.1, the electric schemes from [90] that were used in implementation of this system are presented .

3.2.2 Modeled devices

The current microgrid under construction deviates slightly from the above description. For the research, a fixed configuration of the microgrid is needed to run simulations and comparisons; the above description was used as a basis for the research model. The models of the devices in the simulated research center are divided into three groups: energy sources, energy storage units, energy consumption units (loads). The energy sources comprise [125, 92, 46]:

- Wind turbines – they produce electricity by converting the power of the wind that moves the blades of a windmill. The wind turbine operates within a defined range of wind speeds. The amount of the produced energy depends on the wind speed, the size of the blades and the efficiency of the windmill. Small wind turbines are not able to control their power production, large ones have the ability to change the amount of produced power within a certain range. The wind turbines used in this project have their optimal operating point at 11 m/s wind speed. The minimal wind speed required to produce electricity is 3 m/s. The top speed of wind for this model of turbine is 17 m/s, which is extremely rare case in the area where such turbine is meant to be installed. Power produced by wind turbine is approximated with given polynomial [46]:

  $$P_W(t) = -0{,}0513v(t)^4 + 13{,}182v(t)^3 + 353{,}45v(t)^2 - 1518{,}6v(t) + 2060{,}6$$

  The $v(t)$ is a current speed of wind. In the research center 3 wind turbines are installed, each has power of 10kW, equipped with controllers FKJ-A3 and power inverter WG10K.

- Photovoltaic panels – they produce electricity by converting the power of the solar radiation to electricity. The power produced depends on the surface area of the panel, the efficiency of the process and intensity of the solar radiation. An important element is also the temperature, as the efficiency of the panel decreases with increase of the temperature. Thus, the same panel usually produces more electricity in early spring than during hot summer days. In this project, two sets of panels are considered: one installed on LMEB+LWPE other on LST. Their peak power is 12,6 kW and 10,5kW. The model of the power produced by panels is as following [46]:

  $$\begin{aligned} P_{PV}(t) =& N^{PV} s^{PV} \eta^{PEE} G(t) \eta_0^{PV} \\ & \left(1 + \frac{C_4}{\eta_0^{PV}}\left(u(t) - u_0^{SC}\right) + \frac{C_4 G(t)\left(u_0^{SC} - u(t)\right)}{\eta_0^{PV} G_0}\left(1 - \eta_0^{PV}\right)\right) \end{aligned}$$

  Where: s^{PV} – area of photovoltaic panels $[m^2]$, η_0^{PV} – efficiency of PV given for standard conditions [-],C_4 – temperature constant $C_4 = -0{,}00051/K$, N^{PV} – number of panels, η^{PEE}–efficiency of converter, $G(t)$ – irradiance during time t, $u(t)$ – air temperature [°C], v_0^{SC} – temperature of solar cell [°C], G_0 – solar constant $G_0 = 1000W/m^2$.

- A reciprocating engine – this category includes a combustion engine (a Diesel, a spark-ignition engine) or a gas engine. Although it is not a really an ecological friendly power source, as it requires fuel and pollutes environment, it can generate defined, constant amount of electricity over time. As it is controllable, it is necessary in island mode operation, when reliability of the source is important. Here, the engine is the device that sets the frequency of the current in the microgrid in the case of island mode operation. The peak power of the engine used in this project is 50kW.

- A gas microturbine – the natural gas is considered the most "green" power source acquired out of all fossil fuels and in addition it is also fairly cheap. This solution is even more interesting when the biogas is used. It is assumed here that the gas or the biogas is bought on the market and the accessibility of the fuel is unlimited. The maximum production by microturbine is 65 kW.

- A hydropower plant – the research center is placed near a small river and the original plans included a small hydropower plant. Its production abilities depend on accumulation of water in the water reservoir. In wet seasons the hydropower plant can work with its maximal power, but in situation of a drought the water supply has to be carefully controlled. While the hydropower plant is at the moment not part of the real research center, access to a hydropower plant with 3 Kaplan turbines of 30kW each is still assumed. In the simulation, the 3 turbines will be considered as a one power source of 90 kW. To have a realistic model of water levels, the model of the river is based on the river Świder near Warsaw.

To make the power balancing easier, the following energy storage devices (as in [125, 92]), are considered:

- Flywheels – their efficiency is very high, reaching 93,5%. The electric energy is transformed to the kinetic energy of the flywheel that can turn with the speed up to 60 000 rpm. This is a very fast reacting storage that can even survive short-time overcharge (up to 150% for 1 minute). The power storage capacity is limited by electronic power converter to 50 kW to assure longer time of storing the power, the exact time of storing depends on the speed of discharging and amount of energy physically stored as kinetic energy. In general case the flywheel starts having power losses after 12 seconds, thanks to limiting the storage capacity the time can be prolonged to minutes, depending on the situation. This power storage unit is used as a ultra-fast balancing mechanism.

- Batteries – gel accumulators have efficiency of about 88%, but the charging and discharging power is limited. Batteries are suitable for keeping power for a long time (for days), can be charged and discharged frequently and the density of the stored energy is high. Available batteries have capacity of 50kW.

Apart from sources and energy storage units, the third group of the active elements in the center consists of consumers of electricity, such as refrigerators, computers, lights, air conditioner, special devices for experiments, etc. Considering every single device or socket in the building as a separate power consuming device would be unrealistic, as it would require equipping each device with an energy meter or even a power electronic converter. Such technology is available, but it would be exceptionally expensive to install it in all small devices. In the simulated microgrid, it is assumed that the power is measured in

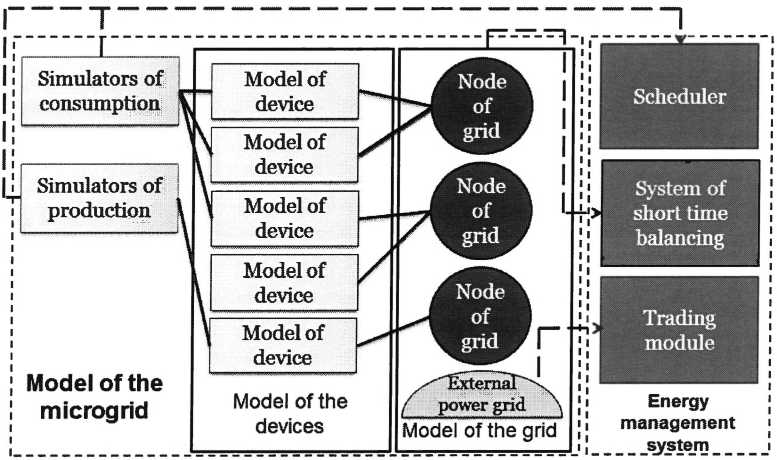


Figure 3.3: General architecture of the microgrid systems.

nodes of the electric installation. The nodes gather several consuming units, for example sockets in few rooms, or the chain of corridor lights.

All of the loads are divided into two groups: the ones that have to be powered in any conditions (unconditionally reserved) and the ones that can be switched off under power deficit (conditionally reserved). If the connection to the external grid is cut, the procedure in the simulation is the same as in the planned center: the microgrid switches to the island mode. The reciprocating engine is switched on and less important circuits are disabled, to keep the core of the electrical system in operation. When the connection to the external grid is restored, the system automatically returns to the default (synchronous) operation mode.

The simulations microgrid combines many devices, most of which exhibit some randomness in their usage: sunshine impacts the photovoltaic cells, wind impacts the turbines, people switch on devices, devices have varying load profiles, etc. To have a realistic simulation, it is necessary to accurately imitate these random factors: they are the biggest hurdle in balancing the power. The generators that were developed within this thesis and used in the research are described in 3.4.

3.3 Energy Management System

3.3.1 Introduction

The aim of the energy management system (EMS) to ensure the efficient and uninterrupted operation of the microgrid. This usually involves production side management and/or demand side management (both described in section 2.2). In this project, another aspect is considered: planning of demand and calculating the reliability factors of elements of the grid. The modeled microgrid has a single owner, and all components are under strict control. It should therefore be possible to schedule events, taking into account the usage of energy.

In order to design an energy management system, several aspects need to be considered. Figure 3.3 presents the simplified environment of the EMS and the main elements of the system.

The system has to base its decision on available information from all possible sources, so the level and accessibility of this information had to be assessed. It is assumed that power can be measured on each node level. The model of the power grid and electric load-flow simulator had to be made to make it possible to calculate the power flows and ensure that there are no violations of physical constraints of the cabling and devices. The load-flow simulator was designed and implemented by group from Warsaw Technical University, the details about implementation and user manual were presented in [83, 84, 85, 89]. More details about the model of grid and devices is presented in [90, 125]. The electric load-flow simulator – the program calculating the flows made by the Warsaw Technical University is shortly described in 3.3.2.

General methods for prognosis of the power usage were developed by team from Warsaw University of Technology and are described in [8]. These prognoses are quite general and provide a good starting point, but are too aggregated to be directly used in a microgrid. In this work, the considered microgrid is a research center and as such, there is some knowledge concerning the activities on specific days or at specific times. Lectures are given, in which case lecture rooms are used (lights, air conditioning), laboratories and workshops are organized (many computers, lights, air conditioning, etc.), events with specific requirements, etc. Some of these events can be scheduled or postponed (e.g. the running of computer simulations). Knowledge about which activities are planned and which activities can be postponed allows for the possibility of better planning the power requirements. Combined with e.g. the weather forecast, this knowledge can allow for a production planning in which the cost of energy is minimized. This planner which deals with this is explained in 3.3.3.

In order to properly design the system, it is necessary to simulate its environment. This includes simulation of the microgrid structure, the operation of devices connected to the network and behaviour of the human users of the devices. Such simulation allow for designing the EMS without the physical microgrid, which in turn also gives opportunity to test cases that would unlikely occur in a live system.

Renewable sources such as wind turbines or solar panels are dependent on the weather conditions, which is the source of dynamic variation of their production level. Models of the devices were described by team of prof. Parol in [45]. To properly simulate the power generated by such sources, first, a model for the devices is needed. To compensate for the variability caused by the weather, one approach is to simulate the weather, and correct the operating point based on the conditions. For this purpose, adequate simulators for solar irradiation, wind and water levels were developed. This will be discussed in 3.4.2.

Simulating the power needed by a node grouping consumer devices can be done by simulating the consumer devices connected to the node and aggregating these results to obtain the value of the nodes. While simulating a consumer device sounds straight forward, it should pointed out that most devices are controlled by people and as such the use of the devices will exhibit a random behavior. Different types of devices also have different power profiles during their operation time, which also needs to be taken into account. Consequently, it is necessary to develop appropriate simulators for devices; this will be covered in 3.4.3.

The system is composed of autonomous subsystems that are connected by exchanging input/output data. A modular approach was used to facilitate research and development. Testing of the separate modules could be done independently, which was especially important as subsystems were developed and implemented by different groups. The overall architecture of the EMS system is presented in fig. 3.4. The most important subsystems are: Load-flow simulator, Planner, Subsystem for short-time energy balancing, Subsystem for energy trading and Reliability factors calculator. The descriptions of the subsystems

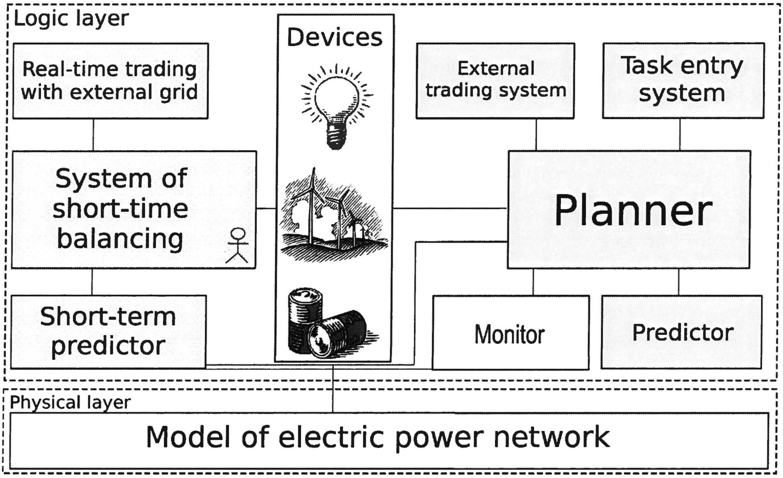


Figure 3.4: General architecture of the microgrid systems.

are presented in next sections.

3.3.2 Load-flow simulator

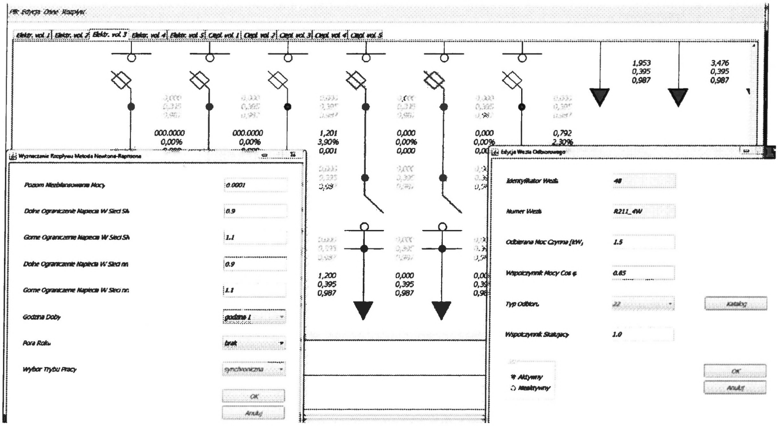
The electric power cannot be treated as a good that can be stored and supplied when necessary. Power flows and the network has to be prepared to take and guide that flow in the right place, considering the parameters of the current. The energy management systems should not only consider the amount of power produced and consumed, but also the way the power flows between the nodes of the network. The research team of prof. Parol (Warsaw Technical University) has designed and developed a program that calculates the flow of power in a microgrid in given circumstances and checks if the physical constraints of the network are not violated.

The program was based on the models of the network and devices described in [90, 91], its operation can be divided into three phases:

- Phase 1. The program reads the default configuration of the power grid; this is defined in the file 'complete_configuration' in the plain text format. The nodes are divided into types, and each node is described according to its type. Four types of nodes are defined: load type, generator type PU (with defined real power and voltage), generator type PQ (with defined real and reactive power) and balancing node. The nodes that contain power storage units as batteries and flywheels are considered alternatively as load type or as generator type. The program reports correct reading of the data.

- Phase 2. The program reads an additional configuration file to update the network status. This file allows the program to recalculate the power grid state just by updating the differences from the previous state. Again, the program reports the readout of the data.

- Phase 3. The program calculates the flow and saves the outcome to the plain-text files, which can be then parsed by the short-time balancing program.



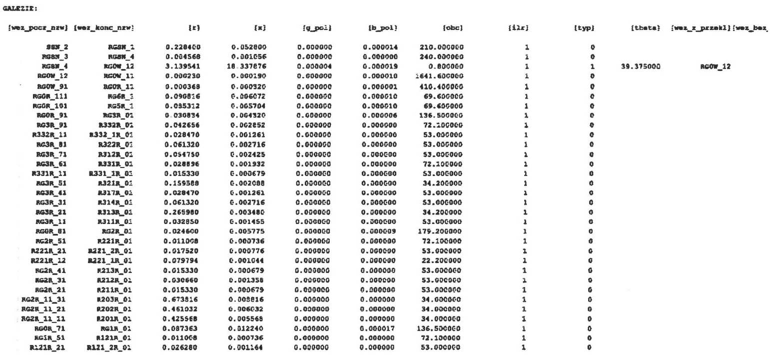
Wyznaczanie Rozpływu Metoda Newtona-Raphsona

Pozom Niezbilansowania Mocy: 0.0001
Dolne Ograniczenie Napiecia W Sieci SN: 0.9
Gorne Ograniczenie Napiecia W Sieci SN: 1.1
Dolne Ograniczenie Napiecia W Sieci nn: 0.9
Gorne Ograniczenie Napiecia W Sieci nn: 1.1
Godzina Doby: godzina 1
Pora Roku: brak
Wybor Trybu Pracy: synchroniczna

Edycja Wezla Odbiorowego

Identyfikator Wezla: 48
Numer Wezla: R211_4W
Odbierana Moc Czynna [kW]: 1.5
Wspolczynnik Mocy Cos φ: 0.85
Typ Odbior.: 22
Wspolczynnik Skalujacy: 1.0
● Aktywny
○ Nieaktywny

Figure 3.5: Graphical user interface (GUI) of the Planner: Definition of power sources with averaged yearly profile of power production by photovoltaic panels.



```
GALEZIE:

{wez_pocz_nzw} {wez_konc_nzw}        {r}         {x}     {g_pol}     {b_pol}        {obc}    {ilr}    {typ}    {theta} {wez_z_przekl}{wez_bez_

        SSN_2        RGSN_1    0.228400    0.052800    0.000000    0.000014   210.000000        1        0
       RGSN_3        RGSN_4    0.004568    0.001056    0.000000    0.000000   240.000000        1        0
       RGSN_4       RGOW_12    3.139541   18.337876    0.000004    0.000019     0.800000        1        1  39.375000       RGOW_12
      RGOW_12       RGOW_11    0.000230    0.000190    0.000000    0.000010  1641.600000        1        0
      RGOW_91       RGOR_11    0.000368    0.000320    0.000000    0.000001   410.400000        1        0
     RGOR_111        RG6R_1    0.090816    0.006072    0.000000    0.000010    69.600000        1        0
     RGOR_101        RG5R_1    0.085312    0.065704    0.000000    0.000010    69.600000        1        0
      RGOR_91       RG3R_01    0.030834    0.004320    0.000000    0.000006   136.500000        1        0
      RG3R_91      R332R_01    0.042656    0.002852    0.000000    0.000000    72.100000        1        0
     R332R_11    R332_1R_01    0.028470    0.001261    0.000000    0.000000    53.000000        1        0
      RG3R_81      R322R_01    0.061320    0.002716    0.000000    0.000000    53.000000        1        0
      RG3R_71      R312R_01    0.054750    0.002425    0.000000    0.000000    53.000000        1        0
      RG3R_61      R331R_01    0.028896    0.001932    0.000000    0.000000    72.100000        1        0
     R331R_11    R331_1R_01    0.015330    0.000679    0.000000    0.000000    53.000000        1        0
      RG3R_51      R321R_01    0.159588    0.002088    0.000000    0.000000    34.200000        1        0
      RG3R_41      R317R_01    0.028470    0.001261    0.000000    0.000000    53.000000        1        0
      RG3R_31      R314R_01    0.061320    0.002716    0.000000    0.000000    53.000000        1        0
      RG3R_21      R313R_01    0.265980    0.003480    0.000000    0.000000    34.200000        1        0
      RG3R_11      R311R_01    0.032850    0.001455    0.000000    0.000000    53.000000        1        0
      RGOR_81       RG2R_01    0.024600    0.005775    0.000000    0.000009   179.200000        1        0
      RG2R_51      R221R_01    0.011008    0.000736    0.000000    0.000000    72.100000        1        0
     R221R_21    R221_2R_01    0.017520    0.000776    0.000000    0.000000    53.000000        1        0
     R221R_12    R221_1R_01    0.079794    0.001044    0.000000    0.000000    22.200000        1        0
      RG2R_41      R213R_01    0.015330    0.000679    0.000000    0.000000    53.000000        1        0
      RG2R_31      R212R_01    0.030660    0.001358    0.000000    0.000000    53.000000        1        0
      RG2R_21      R211R_01    0.015330    0.000679    0.000000    0.000000    53.000000        1        0
   RG2R_11_31      R203R_01    0.673816    0.008816    0.000000    0.000000    34.000000        1        0
   RG2R_11_21      R202R_01    0.461032    0.006032    0.000000    0.000000    34.000000        1        0
   RG2R_11_11      R201R_01    0.425568    0.005568    0.000000    0.000000    34.000000        1        0
      RGOR_71       RG1R_01    0.087363    0.012240    0.000000    0.000017   136.500000        1        0
      RG1R_51      R121R_01    0.011008    0.000736    0.000000    0.000000    72.100000        1        0
     R121R_21    R121_2R_01    0.026280    0.001164    0.000000    0.000000    53.000000        1        0
```

Figure 3.6: Graphical user interface (GUI) of the Planner: Definition of power sources with averaged yearly profile of power production by photovoltaic panels.

The algorithm calculating the power flow takes as an input a vector of states for each node in the grid. A state consist of a vector of absolute value of voltages and the vector of phase angles of voltages. Knowing the vector and given data, it is possible to calculate the power in the branch of the network and the losses of power. Powers and voltages are bounded by equations which take into account the matrix of node admittance. This gives a system of non-linear algebraic complex equation, for which a solution is found using the Newton-Raphson method. In the grid of N nodes and P_{PU} generator nodes, the number of equations is $2(N-1) - N_{PU}$. The method used is an iterative method, where the end condition is reaching a declared precision of calculation in all nodes. The detailed description of the method is presented in [87].

3.3.3 Planner

The micorgrid in the research is a research center, where different tasks have to be performed, and some can be postponed (e.g. a computer simulation). The Planner module analyses the list of submitted tasks and suggests a better time for realizing them, taking into account limitations defined by the user. It was developed by M. Gorczyca, T. Krysiak, M. Lichtenstein and W. Janiak, from Wrocław University of Technology. The model and algorithms for Planner were published in [35, 34, 38, 37]. The outcome of research was computer program that uses heuristic algorithms to schedule defined tasks in such a way, that the cost of operating of the whole research center is minimized. The manual of this program was published in the report [36].

Because the research and conference center considered in the project has specific aim and purpose, the decision was made to limit the use of demand side management or demand response. Demand side management [9] would imply dynamically blocking users of the center from using part of the equipment at some times of the day. The amount of such devices is very limited in the presented situation. The most power demanding devices – research equipment, computer network, conference halls have to be available at any time of the day, which would include peak hours. Demand side management would disrupt the daily operation of the center, and therefor has limited use. However, controlling the usage is one thing and knowing about the events in the considered complex is another. Events like conferences, teaching courses, experiments have their time, place and estimated power usage. Knowledge about such plans can improve the planning of production, battery usage and (if the plans consider the majority of usages) trading with external power network. The Planner was introduced to collect such information and additionally play the role of scheduler, which would at least partly influence the decision of starting some events. The Planner collects data about the events via its connection to the room and equipment reservation system. A user reserving the conference room has to give constraints about the time of the event (lecture, conference, etc.), the system shows the possible choices and the user chooses one of them.

The problem of scheduling the events to optimize the power usage was considered by the team from Wrocław University of Technology as a scheduling multiprocessor jobs problem. The event defined in the system is considered a "job" that has to be done by a number of processors, where a processor is a place/location or a defined equipment. For example the job "seminar" requires a room equipped with the computer and a projector, on the other hand a job defined as a "conference" might require a use of 5 seminar rooms simultaneously. Jobs can have constraints defined: maximum deadline, required time, minimal and maximal number of processors, type of processors, priority, preferred time to start, information about complex jobs (a series of jobs that have to be scheduled one after another). Moreover, the jobs have their power usage profiles and the scheduler has to determine the overall usage of power for the schedule and for each moment calculate the perfect operating point for all power sources. Knowing the operating points, the scheduler can calculate the cost of the schedule, which the Planner is minimizing. In [38], the authors model the problem as a mixed integer programming task, which can be simplified to binary knapsack problem, which is NP-hard. Consequently, the creation of an optimal schedule, considering the cost of power and defined constraints, is a NP-hard problem [33]. In the given scenario, the number of power sources is relatively small and the cost functions of these sources are fairly simple, allowing M. Gorczyca, T. Krysiak and M. Lichtenstein to present a fully calculated optimal solution for a small example.

The algorithm of scheduling the jobs is based on the simulated annealing technique. Simulated annealing [11] is a heuristic algorithm that performs a local search to find a better solution, but is able to temporarily accept worse solutions to allow searches outside of the local optimum. The parameter temperature is controlling the probability of accepting worse solution (than current best solution). In the beginning, when the temperature is high, the algorithm is probing the solution space without focusing on the most optimal values, with lower temperature the algorithm pursues more the direction of more optimal values. It is done to make sure that the algorithm does not get caught in a local minimum in the first iterations, as it might not be the global minimum. The schedule created by the Planner can be suboptimal, but it guarantees to provide a result within a specified time. The schedule includes not only the list of jobs that are executed at certain time point, but also the operating level of all controllable devices in the system. Having such information, it is possible to compute the total surplus or deficit of power in every time period by comparing the planned consumption of power to the expected amount of production.

In Fig. 3.7 – 3.12 the user interface of Planner is presented. Fig. 3.7 presents the interface to define power sources. The uncontrollable sources have their typical, averaged profile for whole year defined. Due to the long term scheduling, such general description is sufficient, especially that the weather conditions can be very quick changing. Small deviations in weather production have to be taken care of by the short-time energy balancing subsystem. Fig. 3.8 presents the sample power functions – it is the profiles that the Planner uses to evaluate how different jobs will use power. The definition is presented as a normalized profile, which can be rescaled to required time period. Fig. 3.9 shows an example of the set of jobs, and an edition screen for one of the jobs. The attributes for a job are: name, date and time when the job can be started the earlies, expected ending date, the type of the processors (places) that can are needed for the job and the minimum and maximum number of processors that can be used to perform a job. In addition, there can be also a priority of the job an and expected time to start a job. Other parameters are power usage (defined as a profile and scaling factor), duration times and an ordering which defines which job should be before and after this job. Fig. 3.10 presents the calculated schedule showing which jobs should be performed on which processors (in which locations). The program also shows the power consumption in scheduled time also how much power is required by each job (Fig. 3.11) and the optimal operating point of the controllable sources in scheduled time (Fig. 3.12). If the schedule is not satisfying the user preferences, the user has to modify the job, by changing the parameters and recalculate the schedule.

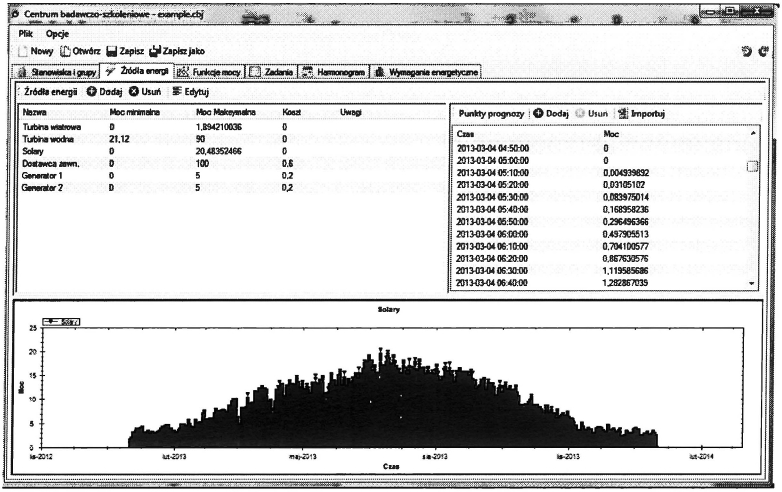
3.3.4 Subsystem for short-time energy balancing

The subsystem for short-time balancing was designed and implemented by author of this thesis under supervision of prof. Z. Nahorski and with help of dr. P. Pałka from Warsaw University of Technology, who helped with the initial design of the agents algorithms. This subsystem is wider described in chapter 5. It is the author's main contribution to the project and forms the core of this thesis.

This subsystem works together with the Planner system - it complements the Planner by balancing the power in the microgrid. While the Planner is making long time schedules, the deviation from the plan are taken care of by the short-time energy balancing subsystem. Balancing is managing the supply and demand of energy in such a way that they equalize at any moment in time. The general project of the algorithm and results were published in [81, 76, 71, 74, 80, 95, 73, 77].

The system uses the multiagent concept 4, as it allows for a clearer understanding of the division of roles in the system and higher level of encapsulation of logic. The agents represent the nodes in the power grid. They negotiate between themselves the flows of power and the operating points of the power sources and power storage units. The algorithm they employ is based on market negotiation, as this approach allows for fast reaching of the agreement.

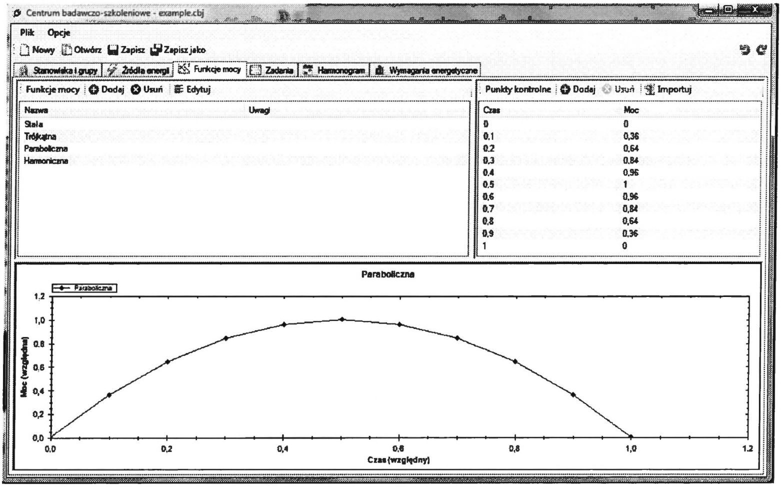
The subsystem uses the power storage units in two ways. Batteries are used as an active balancing mechanism, whereas the flywheels act as a buffer, providing the time for



Nazwa	Moc minimalna	Moc Maksymalna	Koszt	Uwagi
Turbina wiatrowa	0	1,894210036	0	
Turbina wodna	21,12	90	0	
Solary	0	20,48352466	0	
Dostawca zewn.	0	100	0,6	
Generator 1	0	5	0,2	
Generater 2	0	5	0,2	

Czas	Moc
2013-03-04 04:50:00	0
2013-03-04 05:00:00	0
2013-03-04 05:10:00	0,004939892
2013-03-04 05:20:00	0,03105102
2013-03-04 05:30:00	0,083975014
2013-03-04 05:40:00	0,168958236
2013-03-04 05:50:00	0,296496366
2013-03-04 06:00:00	0,497905513
2013-03-04 06:10:00	0,704100577
2013-03-04 06:20:00	0,867630576
2013-03-04 06:30:00	1,119585686
2013-03-04 06:40:00	1,282867039

Figure 3.7: Graphical user interface (GUI) of the Planner: Definition of power sources with averaged yearly profile of power production by photovoltaic panels.

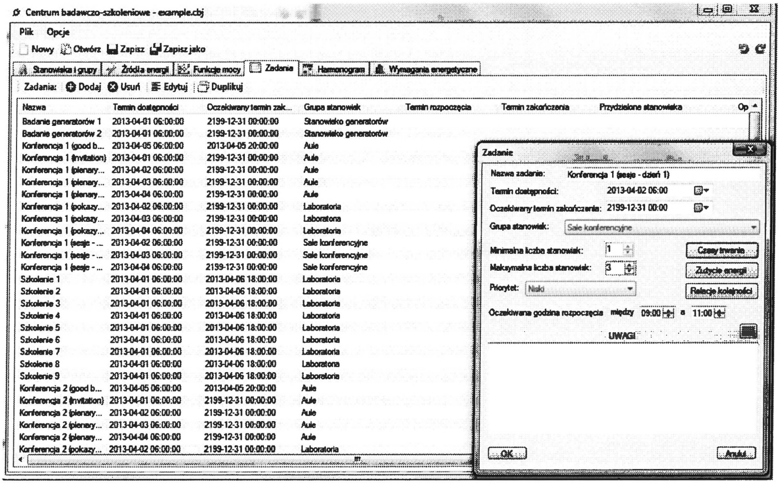


Nazwa	Uwagi
Stała	
Trójkątna	
Paraboliczna	
Harmoniczna	

Czas	Moc
0	0
0.1	0,36
0.2	0,64
0,3	0,84
0,4	0,96
0.5	1
0,6	0,96
0,7	0,84
0,8	0,64
0,9	0,36
1	0

Figure 3.8: Graphical user interface (GUI) of the Planner: Definition of power profile definition for the approximation of consumer usage.

necessary adjustments to operating point of controllable devices.



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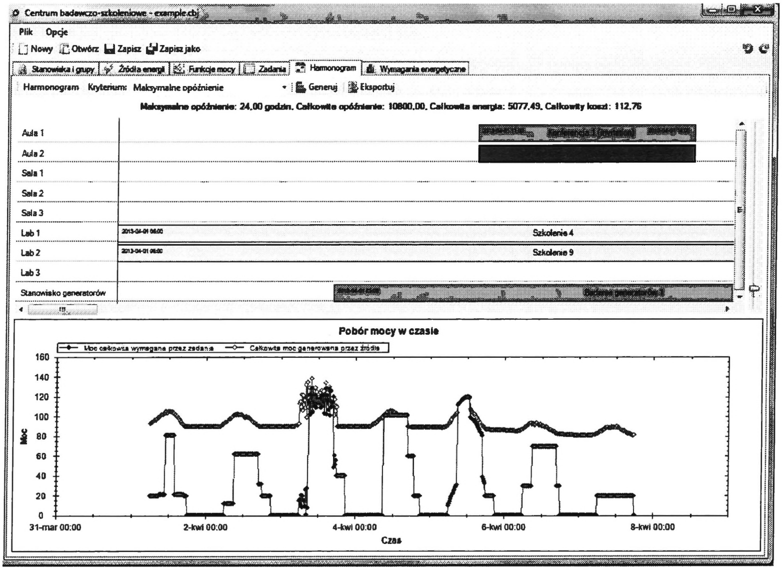
Badanie generatorów 1	2013-04-01 06:00:00	2199-12-31 00:00:00	Stanowisko generatorów				
Badanie generatorów 2	2013-04-01 06:00:00	2199-12-31 00:00:00	Stanowisko generatorów				
Konferencja 1 (good b...	2013-04-05 06:00:00	2013-04-05 20:00:00	Aule				
Konferencja 1 (invitation)	2013-04-01 06:00:00	2199-12-31 00:00:00	Aule				
Konferencja 1 (plenary...	2013-04-02 06:00:00	2199-12-31 00:00:00	Aule				
Konferencja 1 (plenary...	2013-04-03 06:00:00	2199-12-31 00:00:00	Aule				
Konferencja 1 (plenary...	2013-04-04 06:00:00	2199-12-31 00:00:00	Aule				
Konferencja 1 (pokazy...	2013-04-02 06:00:00	2199-12-31 00:00:00	Laboratoria				
Konferencja 1 (pokazy...	2013-04-03 06:00:00	2199-12-31 00:00:00	Laboratoria				
Konferencja 1 (pokazy...	2013-04-04 06:00:00	2199-12-31 00:00:00	Laboratoria				
Konferencja 1 (sesje - ...	2013-04-02 06:00:00	2199-12-31 00:00:00	Sale konferencyjne				
Konferencja 1 (sesje - ...	2013-04-03 06:00:00	2199-12-31 00:00:00	Sale konferencyjne				
Konferencja 1 (sesje - ...	2013-04-04 06:00:00	2199-12-31 00:00:00	Sale konferencyjne				
Szkolenie 1	2013-04-01 06:00:00	2013-04-06 18:00:00	Laboratoria				
Szkolenie 2	2013-04-01 06:00:00	2013-04-06 18:00:00	Laboratoria				
Szkolenie 3	2013-04-01 06:00:00	2013-04-06 18:00:00	Laboratoria				
Szkolenie 4	2013-04-01 06:00:00	2013-04-06 18:00:00	Laboratoria				
Szkolenie 5	2013-04-01 06:00:00	2013-04-06 18:00:00	Laboratoria				
Szkolenie 6	2013-04-01 06:00:00	2013-04-06 18:00:00	Laboratoria				
Szkolenie 7	2013-04-01 06:00:00	2013-04-06 18:00:00	Laboratoria				
Szkolenie 8	2013-04-01 06:00:00	2013-04-06 18:00:00	Laboratoria				
Szkolenie 9	2013-04-01 06:00:00	2013-04-06 18:00:00	Laboratoria				
Konferencja 2 (good b...	2013-04-05 06:00:00	2013-04-05 20:00:00	Aule				
Konferencja 2 (invitation)	2013-04-01 06:00:00	2199-12-31 00:00:00	Aule				
Konferencja 2 (plenary...	2013-04-02 06:00:00	2199-12-31 00:00:00	Aule				
Konferencja 2 (plenary...	2013-04-03 06:00:00	2199-12-31 00:00:00	Aule				
Konferencja 2 (plenary...	2013-04-04 06:00:00	2199-12-31 00:00:00	Aule				
Konferencja 2 (pokazy...	2013-04-02 06:00:00	2199-12-31 00:00:00	Laboratoria				

Zadanie

Nazwa zadania: Konferencja 1 (sesje - dzień 1)
Termin dostępności: 2013-04-02 06:00
Oczekiwany termin zakończenia: 2199-12-31 00:00
Grupa stanowisk: Sale konferencyjne
Minimalna liczba stanowisk: 1
Maksymalna liczba stanowisk: 3
Priorytet: Niski
Oczekiwana godzina rozpoczęcia między 09:00 a 11:00

Figure 3.9: Graphical user interface (GUI) of the Planner: Main screen for defining a job.



Kryterium: Maksymalne opóźnienie

Maksymalne opóźnienie: 24,00 godzin. Całkowite opóźnienie: 10800,00. Całkowita energia: 5077,49. Całkowity koszt: 112,76

Figure 3.10: Graphical user interface (GUI) of the Planner: Sample schedule calculated by the Planner.

3.3.5 Subsystem for energy trading

The microgrid defined in the project cannot be fully self-sustainable, as the planned production abilities are much smaller than the possible peak consumption. This implies that

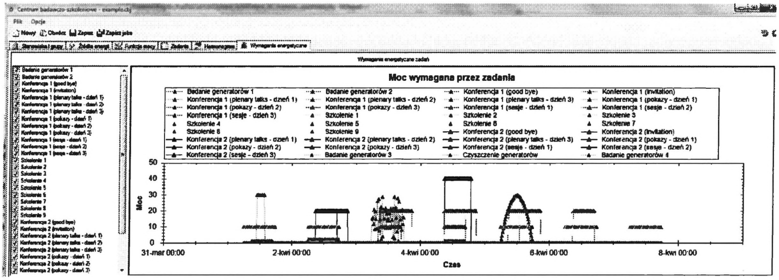


Figure 3.11: Graphical user interface (GUI) of the Planner: Energetic requirements of each task in scheduled period.

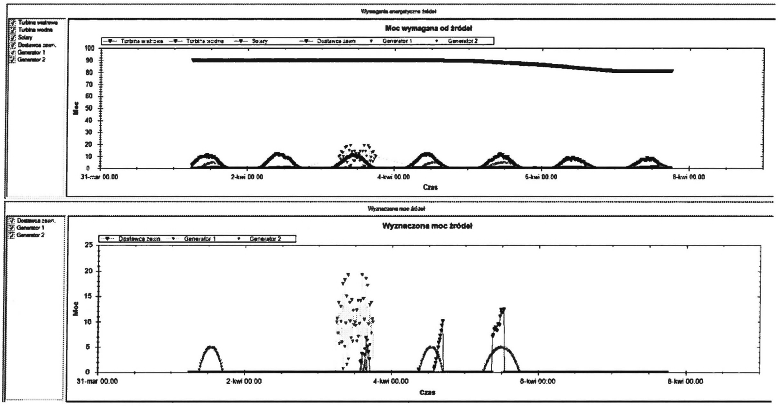


Figure 3.12: Graphical user interface (GUI) of the Planner: Sample schedule of operating points of the power sources that should be set to optimize the cost of power.

the microgrid will have to trade with the external power network. Presently, the only way the microgrid can trade power is by making deals with the power provider. The estimated amount of power that can be produced in perfect weather conditions and with all power sources switched on, is around 250 kW. The possible consumption can reach twice that value (in the project the sum of maximum consumption for each node was estimated to around 950kW, which is nearly impossible to happen). The real difference between production and consumption of power is expected to vary between a small overproduction (in which case power has to be sold to the power grid) and a deficit of power that has to be compensated by the power from the network. The amount of traded power would be relatively small, up to 200 kW. Deals of this magnitude are priced according to fixed tariffs. When the power taken from or sent to the network is significant (several MW), there is a possibility to negotiate bilateral contracts between the power provider and the owner of the microgrid. Such deals can be very profitable and made for a specific situation (e.g. there can be a deal to deliver 1 MWh power by the provider from Monday to Friday for four hours a day from 10:00 – 14:00), but such deals are extremely constrained: for every deviation from the plan there is a penalty fee. The minimal amount of power and the constraints limit the applicability of such contracts. With the popularization of microgrids, an automatisation of trading such deals might become available in the future, also when smaller amounts of power is traded. Good forecasts and maintaining the surpluses and deficits of power within the desired limits might help negotiating these types of contracts.

Potentially the most profitable way of buying and selling energy is participating in the power market. The power markets have a complicated structure due to the properties of the power. Electric power is a special type of commodity: it cannot be easily and losslessly stored, supply and demand have to balance and the availability is changing in time. To manage the balancing problem, the power is traded on different levels: there is a long-term market, where bilateral deals are made; there is so called real-time market, where power is traded on a stock market; and there is a balancing market where the occurring imbalances are settled. The detailed description of power markets can be found in [70, 93, 115]. The future of the energy markets seems to go towards trading even smaller amounts of power. There are concepts of virtual power plants (VPP) and virtual prosumers (VP) – they are units that would combine the power from a number of small sources and microgrids and present them on the power market to make it possible to reach more preferable prices. Such ideas are broadly researched in literature e.g. [78, 16]. Presently, the idea of microgrids and virtual prosumers is still not widely implemented so it is too early to consider the power trading on such small scale. In some countries there are still no settled rules and regulations about a small microgrid taking part in the power market. The future trends show that this might change – there are projects of introducing power markets open to wider number of participants.

Because of this limitation, the work considered in this subsystem of energy trading considers general role of the microgrid in the market. It was assumed that the microgrid offers too little power to influence the structure and prices on the market. In this case, the prices on the market were modeled using neural networks and the price of the power from the external power provider more or less fluctuated with this pattern. The presented module considered the possible future market that allowed for negotiable power trading of low amounts of power.

Additional work should be done in this sector to allow for more intelligent dealing with an external network. The subsystem for energy trading is a module that should advise the users what would be the most beneficial trading strategy on the power market. Due to time constraints the module was limited to description of the model and simulation the prices on such a market. The module was described in details in [111].

3.3.6 Reliability factor calculator

The uninterrupted operation of the microgrid controllers as well as the energy management system is necessary to maintain continuous operation of devices in the microgrid and to maintain proper quality of electric current. The complexity of the grid and the large number of different elements make the problem of reliability important, but also very complex. A failure of a component can have many reasons, but it will always add disturbances to the operation of the microgrid. Reliability factors were developed to characterize the operation of the research center grid, based on the model of the grid described in [91]. In [59] the reliability factors are considered in the reliability factor calculator were presented. This calculator consists of two modules: one defines the topology of the network, the other estimates the parameters using Monte-Carlo simulation methods combined with interval estimation [61]. The full description of the work done in this module can be found in [60, 88, 86, 62, 63].

3.4 Generators of supply and demand

3.4.1 Introduction

During creation and testing of an EMS it is necessary to simulate its runs for longer periods and multiple instances, in order to gather statistically significant information on time and accuracy of balancing the energy. The simulations cannot use a purely random input, as this might yield very unrealistic changes that are impossible to occur in real life. On the other hand, there should be enough variance in the data to allow for many scenarios to be tested. Ideally, it should even be possible to create scenarios.

Many renewable sources are dependent on weather (photovoltaic panels, wind turbines), but available meteorological data are usually insufficient for such simulations. Detailed weather data was available for ten years, but this still limits the number of scenarios that are contained in it. From this rather short period of measurements, a method for generating artificial weather data was necessary. A bootstrap [23] is a method for simulating an 'artificial' data set by resampling original data and then create an arbitrary number of new data, whose statistical distribution are similar to the original ones. The main problems spotted in early tries of using this method to generate time series were the lack of continuity between the parts of data and the inability of recreating long-range trends and dependences. The Matched-Block Bootstrap (MABB) method proposed in [24], and later described in [13] introduced matching blocks (a piece of time series of certain length) to select the consecutive block in the new series. [106, 50] introduced the k-nearest neighbour bootstrap, where blocks from the k best matching years are sampled randomly. [110] proposed to use squared differences of the last values in the blocks as a matching factor, which influences probability of choosing the block. For the purpose of simulating the power production by renewable sources, a fitness proportionate selection method (also known as roulette wheel) [7] to choose blocks for creating the simulated data is proposed. It is a non-parametric and computationally non-demanding method to create input data of any required length, using a limited number of original data. The technique and results of the application of this new method on real data are included in subsection 3.4.2.

In literature, simulators of consumed energy are usually simple, as the main effort is channelled toward creating management systems for the next generation of electric networks. They usually are based on general profiles collected from few devices. Each device has its own profile of energy requirement that varies in time. The amount of energy used by given equipment can be measured, but the general, statistical data of how frequently and how long people use devices are missing. Attempts have been made to measure the average amounts of power that different groups of consumers use during longer periods of time. A report about the energy usage in Spain [1] is the most complete in that field (in [120], a short summary of the [1] is presented in English). Due to huge differences in culture, climate and wealth of the regions, the results of such research are not applicable to other geographical locations. Lack of such detailed data makes the simulation of consumption in other regions difficult. A more general approach, which does not rely on such detailed data, is to simulate the user behaviour. The models and software to achieve this, developed within this thesis, are described in subsection 3.4.3.

3.4.2 Power supply generator

Data sets To be able to simulate power supply from renewable sources, detailed weather data was needed. These data sets were obtained from LAB-EL Elektronika Laboratoryjna [48], a producer of weather parameters measuring equipment, which has a meteorological station near Warsaw, in Central Poland. Out of many parameters measured, particularly interesting for this study were the irradiance, temperature and wind speed.

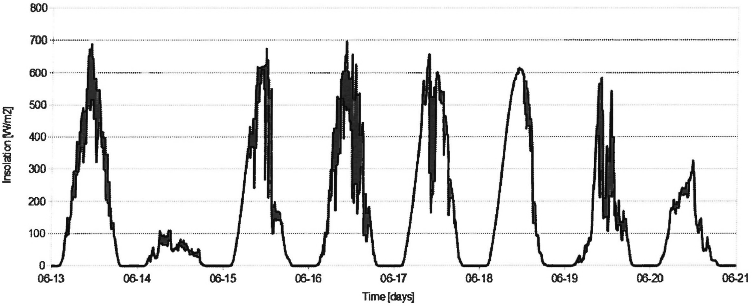


Figure 3.13: Example of measured sun irradiation during few days in June 2010.

Irradiance is the power of electromagnetic radiation per unit area incident on a surface. The irradiance was measured using meter LB-900 [48]. The sensor is equipped with photodiode sensitive to visible light. Data are available for 9 full years (from 2004 till 2012), in a 10 minute interval. An example of sun irradiance for a few days in June 2010 are depicted in Fig. 3.13, where the changeability of the solar power measured by the sensor can be seen. Cloud cover is an important factor that influences the amount of sun radiation reaching the ground level. The influence of cloudiness is big and cloudy days can be in the vicinity of sunny ones, which makes the irradiance modeling not that straightforward. Unfortunately, there are very scarce data about the type and dynamics of clouds that could be used for modeling purposes. Due to the fact that clouds move and have different transparency, there is a lack of mathematical methods for irradiance simulation. In [82] the irradiance is forecasted using the Weather Research and Forecast (WRF) model, where radiation interactions with air, steam, clouds and climate profiles of ozone and aerosols are considered. The location described in the article is the Atacama Desert, where the influence of clouds and humidity is extremely limited. In this article we use the data about the irradiance measured directly, so no model for cloud cover is necessary.

Temperature is an important factor for photovoltaic panels efficiency. A change of temperature has a small, but still visible impact on the electricity production of the panel. A difference in temperature of 60 degrees Celsius (from -25 to +35) makes a difference of 500W in produced power for 15kW panels, presented in Fig. 3.14. For comparison, the change of irradiance necessary to cause a similar effect is 30 W/m^2. The dynamic of temperature changes is slow and shows very strong seasonality, with averages similar in different years. Taking into account its small impact on power production and visible seasonality of the data, it was decided not to include the strict dependence on the temperature in the generator, and use only the average temperature for the considered day of the year.

The amount of energy produced by a wind turbine depends on the wind speed, the size of the blades and the efficiency of the wind turbine. The required start-up wind speed for the turbine used in our study is 3 m/s, and the optimal wind speed is 11 m/s. The obtained data on the wind speed were available over 10 years, from 2002 to 2012 in 10 minute intervals. Wind does not change much between the 10-minute periods, in 19% of the measurements the wind does not change, in 21% it changes by 0.1 m/s. In rare cases, the changes might reach even 1.2 m/s, which shows that although the wind is blowing with more or less constant speed, sudden changes can happen. Central Poland is not a very windy region: most of the time the speed of wind varies between 2 and 4 m/s.

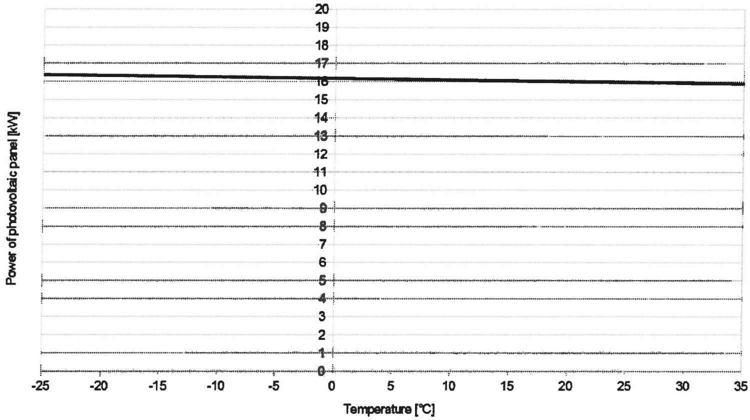


Figure 3.14: Change in production of electric power by the photovoltaic panel in different temperature.

Research about water flow is extremely important as the water can become great destructive force; its level and dynamic are therefore monitored. There are a lot of publications about water forecasting and modeling of rivers and water reservoirs. Here a small power source is considered, so the focus is on a small river. For the requirements of the project the small river – Świder, in the vicinity of Warsaw was chosen. Świder is a river in Masovia and a tributary to the Vistula. It is a river of length about 89 km with average water flow of 4,86 m^3/s. Data were obtained from Institute of Geophysics, Polish Academy of Sciences. Data are from 48 years, from 1961 to 2009, one measurement per day, indicating the amount of water flowing via the river.

Generator architecture The Matched-Block Bootstrap was originally used to multiply the amount of data for statistical analysis, here the technique is used for the creation of new time series from the obtained measurements. The generated time series should have similar statistical properties as real measurements. The method concatenates blocks (which are pieces of time series of certain length) to create a new series of data of required length [25, 40], as presented in Fig. 3.15. Weather time series are subsequent measurements with time indication; these types of data are continuous in time. To keep the connection between the concatenated pairs, the joining points should be as close as possible, so blocks with similar values at the end and beginning should be chosen with higher probability. The upper figure shows part of the original time series of wind speed; the lower shows a part of the generated time series made up of concatenated parts from the upper series. Equal length blocks are considered.

Determining block length Irradiance data has some properties that require a change to approach: data of irradiance are time series with clear cycles of 24 hours. The most intuitive approach was to define a block as a 24 hour period starting from 0:00 and finishing at 23:59. The problem is that values near to the end and beginning of the block have always value 0. This makes the methods of matching consecutive blocks by similarities of the end parts equivalent to a random draw with uniform distribution. The matching factor is therefore defined as the value of correlation between irradiance sequences in two

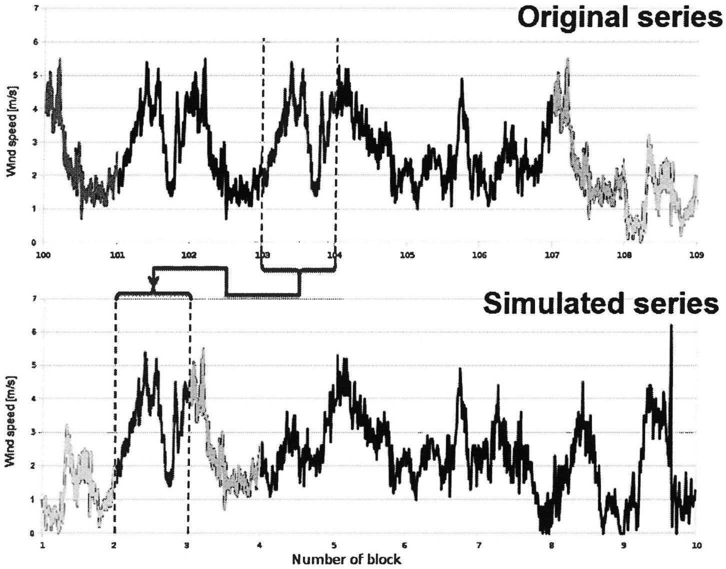


Figure 3.15: The schema of the Matched block bootstrap presented on wind example. The upper time series is the sample of wind speed data, the lower is a bootstrapped time series.

subsequent days of the same year, calculated as ensemble estimates. This correlation is also used as a probability of taking the next day from the same year in the selection method with the inversion operation, described in the next section. The correlation estimates between subsequent days is presented in Fig. 3.17.

Choosing the proper length of blocks is important. It is strongly related to the type of time series that is considered. The matched block bootstrap method requires fixed time period blocks to be chosen from different years, that will be later on concatenated together to create artificial data of the required length. For the wind, the block length had to be correlated with the dynamic of wind speed change. In a literature, short-term wind speed forecasting for wind ranges from 1 to 10 hours ahead [129]. This gives the boundaries to the search for the optimal length of time period used in the proposed method. The autocorrelations of data were calculated for a number of different periods. The outcome was that the loss of correlation rises with the time shift, so the period length of 5 hours has been arbitrary chosen. The correlation values between 5 hour blocks are presented in Fig. 3.16. The matching factor (called also a "feature" in literature) of blocks is defined as the squared difference between the end of the blocks at the same time of a year:

$$d_{i,j} = (r_{i,t} - r_{j,t})^2 \tag{3.1}$$

where i and j are the numbers of the year, and $r_{i,t}$ and $r_{j,t}$ are the last values in the blocks from the years i and j, respectively.

Choosing the length of block for water was the most difficult as no patterns could be discerned. This is due to the very abrupt changes of water level as can be seen in Fig. 3.18, so an arbitrary block length of 25 days was chosen.

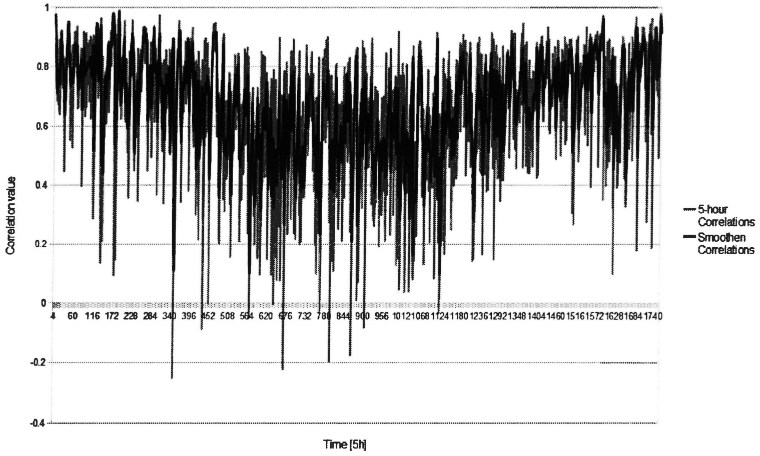


Figure 3.16: The correlation between blocks of 5-hour length for wind data.

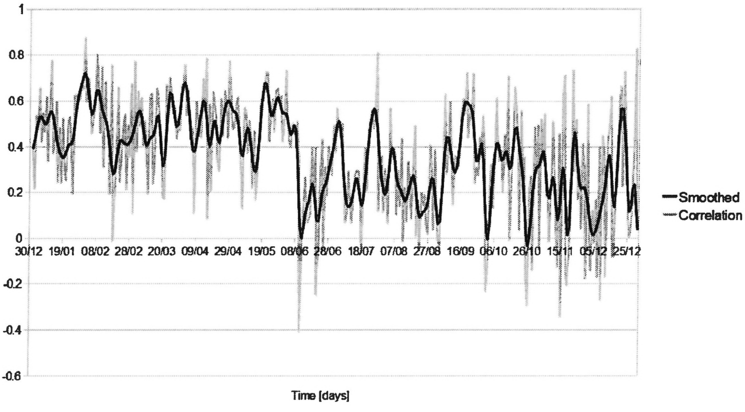


Figure 3.17: Estimates of correlations between two subsequent days for solar irradiance, averaged over all available years (from 2004 to 2012); to increase readability smoothed values of correlation are also presented.

Fitness proportionate selection The MABB method implemented for the purpose of this research is a modification of the one described in [110]. The idea in that article is to choose the next block out of k nearest neighboring blocks, as proposed by [50]. However, Lall & Sharma used equal probabilities for the choice, while the aforementioned authors use uneven probabilities, dependent on a match of the blocks. The idea applied and presented here is to use the fitness proportionate selection for choosing the subsequent blocks out of the candidates from all years. The method groups the time series by month, day and time.

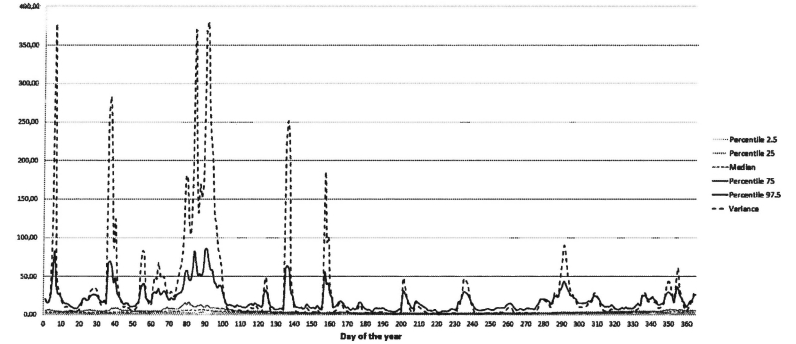


Figure 3.18: Yearly minimal, median and maximal flows of Świder river from 1960/11/01 to 2010/10/31.

Each year of real measurements is treated as a separate source data. The next block is chosen from the set of blocks with the same time stamp.

The fitness proportionate selection method (often called the roulette wheel) was introduced as a genetic operator for choosing individuals for creation of a set of descendants in genetic algorithms. It assigns a probability to each individual considering its value of a so-called fitness function, which in our case will be connected with the matching factor. The better the match of the individual, the higher its probability of being chosen. The sum of probabilities of choosing all individuals has to be equal to 1, which requires a normalization of the fitness function values. The main feature of the roulette wheel is that even the least fitted individuals have still a small chance of being chosen. This gives better variability to create a series of fairly well matching blocks. This is a desired feature in the generation of time series data for our purpose, as a small amount of unusual weather conditions improves relevance of testing cases, and therefore its statistical properties in the probability distribution tails. To create the weather generator, two functions were proposed for transforming the matching factor (where a smaller factor value means better matching) into a fitness function (where a higher value means better fitness). One is using the inversion operation, the other is using a fuzzy set negation operation, where the factor is normalized and subtracted from 1. In both cases, it is then normalized to the [0,1] range. The squared difference is taken as the matching factor. The methods are described in more detail in the following subsections.

Fitness proportionate selection with inversion operation The smaller the squared difference between the blocks ends $d_{i,j}$, the higher the probability of choosing the block should be. In the first selection method the following operation is applied:

$$D_{i,j} = \frac{1}{d_{i,j}}, \; d_{i,j} \neq 0 \tag{3.2}$$

To get probabilities, these values have to be normalized to the range [0,1]. The normalized values are denoted as $p_{i,j}$:

$$p_{i,j} = \frac{D_{i,j}}{\sum D_{i,j}} \tag{3.3}$$

Each value represents the probability of choosing the j-th block as the succession of the i-th one. The smaller the difference $d_{i,j}$ is, the bigger the probability $p_{i,j}$ of choosing the

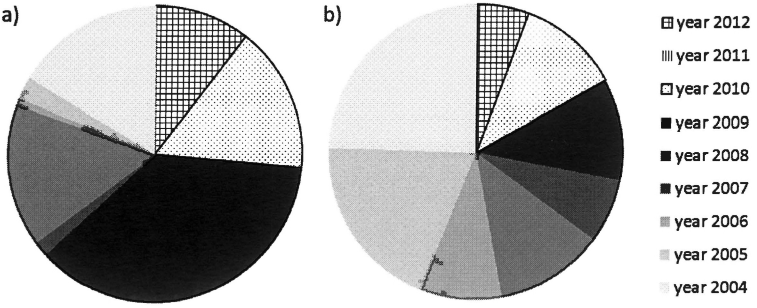


Figure 3.19: Examples of fitness proportionate selection with inversion operator for irradiance for a) 10 Jan 2011 and b) 10 June 2011. Segments represent the probability of choosing the block from a given year

block as a succession. Examples of the sample fitness proportionate selections with the inversion operation are presented in 3.19.

Fitness proportionate selection with the inversion operation has a major drawback. The difference between consecutive blocks from the same year is always 0, and cannot be inversed. To solve this problem, the decision is done in two steps. The first step of the decision is, if to continue with the next block from the same year or not. The probability of choosing the block from the same year is defined by the absolute value of correlation between the currently chosen block and the successive one. The answer "yes" terminates the procedure. If the answer is no, then in the second step the inversion selection procedure is applied without the successive block from the same year. If the difference between the blocks is less than or equal to 0.1 (the accuracy of the measurements), the arbitrary value $D_{i,j} = 10$ is chosen.

Fitness proportionate selection with negation operation To avoid problems with undefined values, another fitness proportionate selection, with negation operation, is introduced. In this method the squared difference between blocks is transformed according to the following equation:

$$n_{i,j} = \frac{1}{N-1}\left(1 - \frac{d_{i,j}}{\sum d_{i,j}}\right) \tag{3.4}$$

where N is the number of possible choices of blocks. The values $n_{i,j}$ are normalized to the range $[0, 1]$. Each normalized value is the probability for choosing the block from a given year (denoted as i). In this case the decision is taken in one stage. An example of an outcome of this method is presented in 3.20. This selection rule results in more even distribution of probabilities compared to the previous one.

Irradiance generator Generated data of solar irradiance statistics are depicted in Fig. 3.21. The sample mean, standard deviation, skewness, autocorrelations and histogram are close to their counterparts from real values, values are presented in table 3.1.

Wind speed generator For the wind speed, the statistics are presented in Fig. 3.22 and in table 3.2. The statistics for the generated and real data are very close. Comparison of frequency of wind speed values revealed that generated time series tend to be less extreme than the original one. The wind speeds between 0.4 to 5 m/s tend to be equally

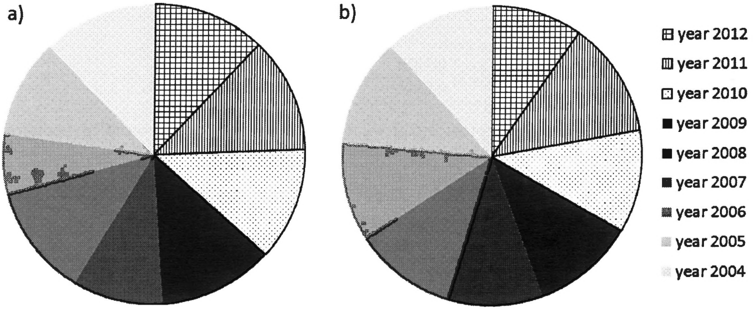


Figure 3.20: Examples of fitness proportionate selection with negation operation for irradiance for a) 10 Jan 2011 and b) 10 June 2011. Segments represent the probability of choosing the block from a given year.

	Mean	Median	Autocorrelation	Skewness	Std. deviation
Inversion	96.4	2.62	0.81	0.59	162.5
Negation	96.7	2.63	0.79	0.59	163.45
Real data	97.6	2.73	0.81	0.6	162.69

Table 3.1: Statistics of real measurements of irradiance compared to generated by bootstrap using two methods of block matching.

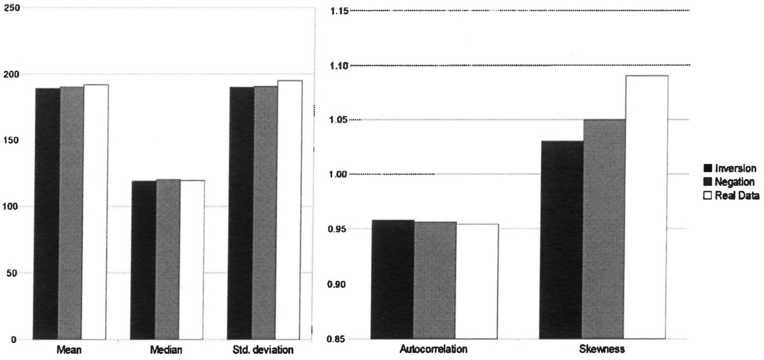


Figure 3.21: Statistics of the generated irradiance.

frequent for all methods, but the wind speeds greater than 11 m/s appeared with much smaller probability using inversion selection method and did not appear at all in negation selection method. Because such values appear extremely rarely (few times in all real time series) it is not invalidating the method and does not influence the statistical qualities of the methods, see in Fig. 3.23. The results indicate that choice of the selection method is not very important. Inversion operation creates time series that have slightly better statistical qualities, but have a tendency to continue with the same year, if the correlation between the consecutive blocks in some time of the year is high. The negation operation

	Mean	Median	Autocorrelation	Skewness	Std. deviation
Inversion	2,5506	2,31	0,5451	1,70344	1,4991
Negation	2,5602	2,31	0,1351	1,6989	1,5072
Real data	2,6007	2,3	0,6302	1,6887	1,5465

Table 3.2: Statistics of real measurements of wind speed compared to generated by bootstrap using two methods of block matching.

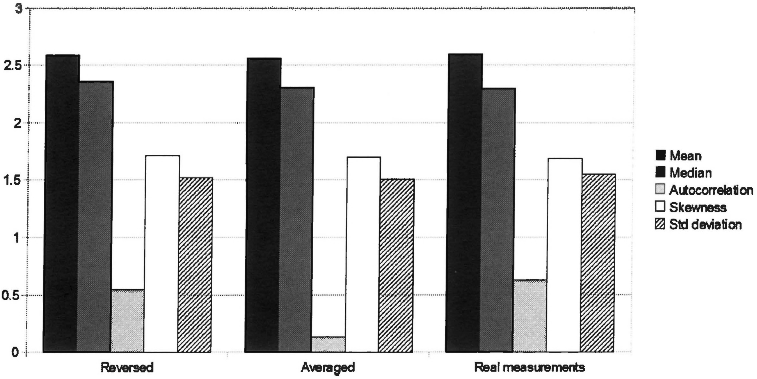


Figure 3.22: Statistics of generated wind speeds as compared with the real data statistics.

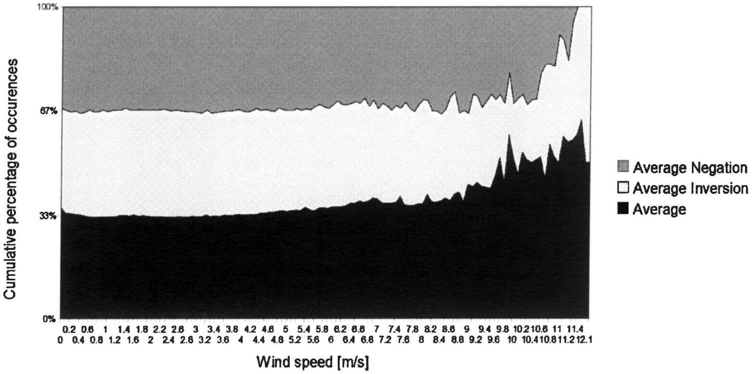


Figure 3.23: Proportion of occurrences of wind speeds in two generated and real measurement sequences .

chooses the blocks from different years more often. The method using negation operation results in more typical and averaged time series, but the extremes are still present.

Water flow generator Statistical characteristics of generated water flow data are very similar to real measurements of water, as presented in table 3.3 and in Fig. 3.24. Due to the extreme skewness of values for water flow and the fast changes, using the bootstrap

	Mean	Median	Autocorrelation	Skewness	Std. deviation
Inversion	4.33	2.86	0.88	1.03	4.9
Negation	3.91	2.71	0.87	1.02	4.12
Real data	4.27	2.24	0.91	0.77	4.24

Table 3.3: Statistics of real measurements of amount of water compared to generated by bootstrap using two methods of block matching.

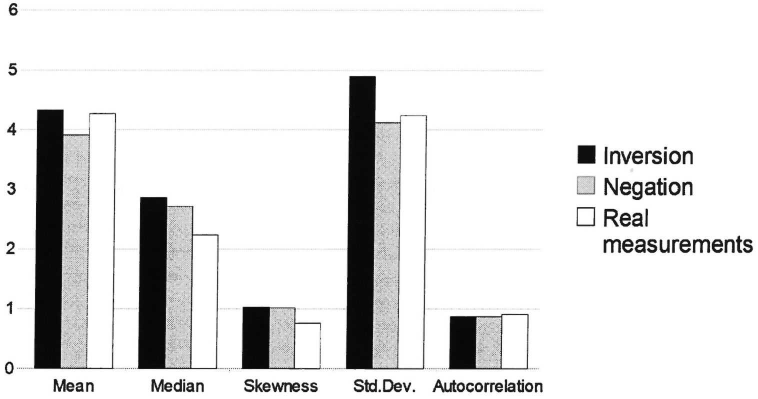


Figure 3.24: The basic statistic of generated and measured statistics of the water.

method for water seems less appropriate than it is for wind speed and irradiance, but it still seems sufficient for the use of the supply generator.

3.4.3 Power consumption generator

Power production has to cover demand and has to compensate for power loses – this balance is crucial for the operation of the networks. If we look from the point of view of high voltage networks, the problem can be solved on the level of automatic sensors that would measure certain parameters of the current. On this level the aggregation of consumers and producers is such that only the major imbalances are considered.

When the only sources of power were huge electric power plants, management of power in the network was relatively easy. The flow of energy was mainly unidirectional and the power production was centralized, which made it easier to manage the power production. But the constantly growing demand for power forced network to undergo constant modernization. With a rising demand, the prices went up; they increased even more when the world became aware of the ecological problems, in which energy producing sector has its part. Introducing more ecological solutions lead to fragmentation of power sources which required to more advanced power balancing systems.

The undergoing changes are not just in the area of energy production. Increasing prices and ecological awareness changed the way that people think about consuming energy. The energy consumption has become an important factor that influences the purchase of new appliances, partly due to clear labeling of the average energy usage. The technology of production of most of daily use devices is evolving toward more energy saving solutions, like for example incandescent light bulbs are being replaced by the fluorescent lamps and by light-emitting diode lamps (LED).

With the development of smart grids, the ideas for optimizing energy consumption went even further: to ensure the stable parameters for current and to ensure rational prices for power, the consumers should actively take part in managing the energy usage. A new interdisciplinary research area called Demand Side Management (DSM) emerged. DSM has several main goals: to convince people to take part in energy optimization, to find the best way to communicate them the current status of the network and to develop appliances that would optimize power usage without the human intervention.

The first problem lies in showing people the problems and making them realize that they can make a difference. However, such actions requires that people adjust their lifestyle to the current situation. If there is a peak of demand, the more people should shift their energy consumption (by e.g. not switching home appliances or postponing cooking their lunch) and the cheaper and easier would be to cope with peak effects (usually additional power sources have to be switched on just to cover short term demand increase). The second problem is in the communication of the network status: how can the users know that there is deficit of power? The most popular way of informing people is by prices. When there is peak of consumption the price of energy is high and it is lower when there is an excess of energy. That idea was behind introducing peak and off-peak tariffs.

To simplify the consumption management, there is the idea to create intelligent appliances that would actively delay or modify their operation cycles to reduce the power peak. Such devices exist (e.g. some washing machines by Miele), but they are still very unpopular due to lack of trust of people – they do not like the feeling that something is happening outside of their knowledge – which partly is caused by the lack of understanding of how such systems work and what they do.

The biggest obstacle for introducing DSM technologies, is the lack of preparation of the legislation that would allow introducing retail market, setting clear rules about exchange of information from smart grid, introducing simpler rules of installation micro sources (both renewable and not), etc.

The problem of demand management is extremely important as the consumption control and forecast facilitates the power balancing. To test the system of power balancing, it was necessary to create a simulation of the operation of the conference center which implies simulating power demand in frequent intervals for each node of the network. Simulation of energy consumption is complex, as there usually is a large number of heterogeneous loads considered. Consumers can be considered at different aggregation levels: from models of single devices, over nodes of the network, to whole buildings and bigger structures as areas and cities.

For households, small microgrids or single buildings, individual devices such as an oven or microwave, are usually considered [120]. Data about their power usage can be measured, which gives exact information about the dynamic of changes, but considering the large numbers of devices of the same type, broad testing is required to derive the generic usage of some appliances. The authors of this work were unable to find any studies concerning the characteristic power usage of basic devices. The exception here is a computer, of which the power usage can be measured on-line and general opinion that computer is consuming a significant amount of power. In larger networks, at levels of groups of houses, general profiles are used (e.g. in [123]), and networks profiles are classified by sectors, such as commercial, residential, industrial.

For some purposes, the general profiles are sufficient, e.g. in [125] they are used to verify the design of the network. This approach was used to verify the designed system for the conference and science center, in order to identify possible overloads or violation of constraints. For this purpose, eighteen typical load-flow calculations were designated, with 19 profiles for different categories of loads. The authors of [125] parametrized a test by:

season (summer/winter), hour (from 11 a.m. to 1 p.m.), type of the day (weekday/holiday), weather conditions (windless and sunless day/windy and sunny day), demand (maximum or minimum) and the state of energy storage units (OFF/charge/discharge). Such parameters combined with power profiles were sufficient to cover all extreme situations, e.g. extremely high consumption with no production from renewable sources. The tests confirmed that the network was well designed and there is no threat of overload. But such load profiles are not good enough to test the dynamic behavior of the microgrid: the values of a profile are 1-hour averages, yielding only 24 different load values for a day.

Profiles for a big group of consumers can be easily derived, as any outstanding or uncommon behaviors tend to be compensated by one another, so they do not vary very rapidly. On country scale, the profiles can be easily obtained from large power producers. The profiles show cycles of daily and weekly changes that reflect the human activities: the night is usually a time of lower energy usage, and usual peak usage is around late afternoon. Weekends and holidays introduce disturbances to the working day cycles. Moreover, seasonal differences are visible, caused by different demands: changes in the outside temperatures (e.g. a large amount of power is used for air-conditioning), long holiday seasons and changes in labor structure [1].

By contrast, in microgrids, each consumer has a relatively larger influence on the profile than in large grids: a 4kW induction cooking plate will not be visible in profile on the regional level, but can dominate the energy usage in a single household. When a single domestic device can make a change, its switch on and off time is visible in the power usage. Averaging power consumption is such situation introduce imbalances, because the usage is changing very dynamically and the most effective would be controlling changes in real time. Thus, profiles are not sufficient for microgrid simulation purposes, because their resolution is usually too small (every hour or half an hour).

The most comprehensive research about the structure of energy usage has been done in Spain [1]. The users presented in the report are divided in 5 groups: residential, commercial, touristic, large consumers and others, with the total contribution of power usage 20%, 6%, 0.5%, 25%, and 48.5%, respectively. These values might differ between regions and countries and depend on the method of categorization. The authors emphasize big differences in the energy usage between user groups, for example households, tourist facilities or companies. Other factors that influence the amount and structure of power usage are e.g. seasons of the year (in the case of Spain there are 2: summer and winter, but it may differ in other climatic zones), days of week, times of day, months, holiday distributions, structure of labor and economic situation. It demonstrates the difficulty to obtain one reliable description of consumer structure even within small area.

The EMS considered in this work governs a relatively small microgrid (see 3.2). The maximum necessary load does not exceed 900 kW. In this situation, a room where a computer lesson takes place can use easily 4.5 kW, which can be visible in overall balance. Such lessons can be planned and entered into the Planner (see 3.3.3) which would inform the energy management system about an increase in power. Power usage of computers in a room, projector, air conditioning and lights are gathered and their average power usage is placed in the schedule for a specific time with a duration of e.g. 1.5 hour. The important thing to remember is that Planner plans energy for the rooms, but one room can be connected to few different nodes: one node would be light, other computers and other general use sockets.

For the Short-Time Balancing System (see 3.3.4), the execution of the task "computer lesson" would mean the increase of power on two nodes of network, the one that would power the computers (which is reserved, i.e. the node has priority in receiving power) and the other for lights and additional equipment. That means that two agents would "sense" the increase of power usage and start the balancing procedure.

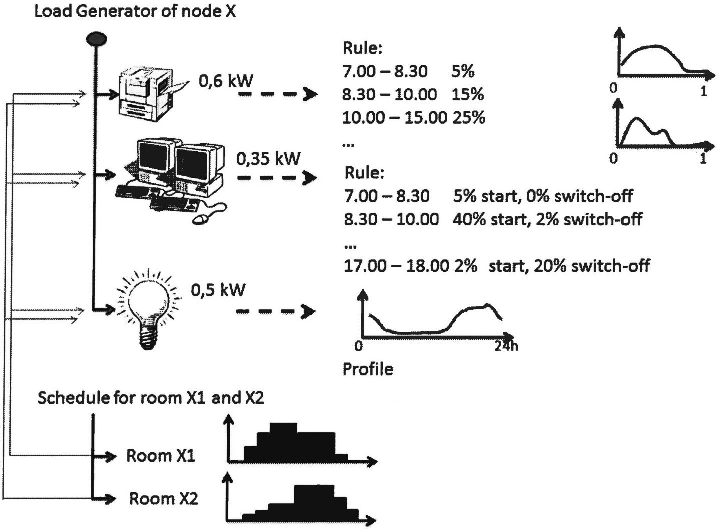


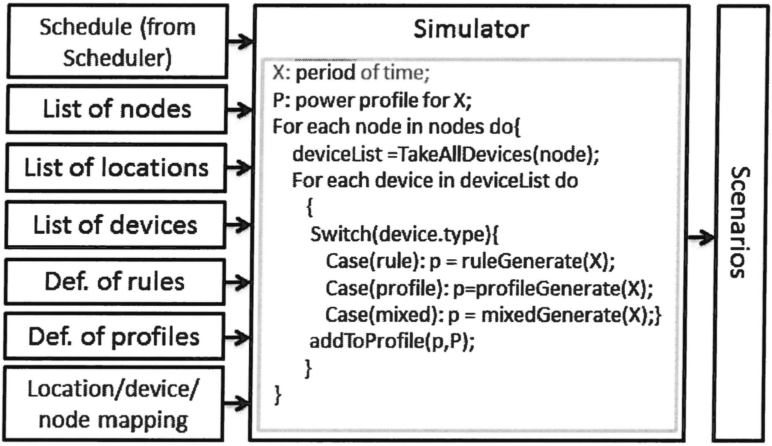
Figure 3.25: A diagram of different possible descriptions of energy consumption.

The goal was to create a load simulation device that would consider the information from Planner (scheduling in which locations the increase of power is expected), but also simulate the general operation of the devices in microgrids (e.g. lights in the corridor, air-conditioning) and simulate randomized behavior of people (e. g. switching on and off computers, making coffee). Because Planner and Short-Time Balancing System are operating on different levels, the simulator has to operate on a common lower level. The most obvious was considering the level of single devices, and use the information about which node a device belongs and in which location it is. There can be a simplification, as some devices are operated together (e.g. lights in a room), in which case it is sufficient to simulate to load on the node rather than each individual device.

Simulating the power usage of each individual device allows for a higher accuracy, makes the simulation less abstract and gives possibility to base the model on existing devices, whose parameters might be measured or found in the literature. In [122] a detailed analysis of representative office environment was conducted to test the model designed; 500 electrical devices were identified, mostly user dependent.

Description of consumer behavior The modeling of users' behavior regarding the use of electric equipment is the most difficult part of the simulation. It is due to a number of factors:

- there is a big variety in peoples' actions due to personal differences, habits, location, time, etc. – research conducted in one location may be not useful in others. This forces to make research on a larger scale and more detailed about the social group, place and time.



```
X: period of time;
P: power profile for X;
For each node in nodes do{
   deviceList =TakeAllDevices(node);
   For each device in deviceList do
    {
    Switch(device.type){
       Case(rule): p = ruleGenerate(X);
       Case(profile): p=profileGenerate(X);
       Case(mixed): p = mixedGenerate(X);}
    addToProfile(p,P);
    }
}
```

Figure 3.26: Concept of the Simulator of consumption with data sources, outcome and general description of the algorithm.

- people do not like to be interrogated – questions about how they use electric equipment during the day would reveal their daily activities, in which case it is unlikely to obtain honest and exact replies,

- behavior of people might be extremely erratic – group of people might have a tight schedule, but their detailed actions will be different each day, that suggest a probabilistic or fuzzy models of such actions,

- constant evolution – the change of technology is extremely fast, even when the people behavior is predictable, the devices their use are constantly being modernized, which for devices as washing machines or fridges is a mater of years, in the area as computers and cell phones might be a matter of year or two, the point is that a once described set of devices might change in few months and for sure it will change in few years. Only the trend of that change can be generally anticipated.

Devices consume power because people connect them somewhere, switch them on and use them. The load simulator, in reality, tries to mimic the patterns of human behavior. It cannot model the whole complexity of human reasoning, but can derive general patterns and statistical distribution of certain human actions.

Concept of the simulator The output of the simulator is generated load data for each node of the network, for a certain period of time, with a given start date and a time and a sampling frequency defined by a parameter. For each node, this will be the aggregated value of the simulated load for all devices connected to the node. The generated data are stored as test scenarios which allows to repeat the test with exactly the same loads, which otherwise would not be possible due to the random factors in the algorithm. Naturally, it also allows to test with different configuration of sources. The schema of the system is presented in Fig. 3.26.

Data that have to be available for the simulator consists of: the schedule made by the Scheduler, the list of nodes with information on how many and what type of devices are

Property	Profiles	Probability profiles	Rules
Duration of operation	long	long	short
Random. of switching on/off	none	high	low
Random. of switching time	none	low	high
Main variability	none	duration	switching time
Example	external lighting	computer	microwave

Table 3.4: Different requirements for different devices in the consumption generator

connected to them, the mapping between devices, nodes localizations (e.g. rooms), the profiles of the nodes and individual devices that are connected to a node, and the rules for devices without profiles.

The simulator processes each node separately, queries all the devices connected to the node and then generates for each device the load for the requested time period. It then sums up all power consumptions of the loads connected to the node, at each sampling time. Each device is processed depending on the type of the device, and the load is generated from the profile or from the rule. The most important factor is the date and the time, as both rules and profiles are parametrized by them.

Different devices have different usage patters. To simulate all of them, four different approaches were considered:

- Profiles
- Probability profiles
- Rules
- Combined rules with short profiles

Table 3.4 summarizes the different aspects of the first three of these approaches. The approaches match different usage patters for devices; the last approach allows for a combination of the first three methods; which allows for a very realistic simulation of the consumption. Each of the methods will be described in detail in the subsequent sections.

Profiles The usage of energy by some devices can be described as a profile, which approximates the function of energy usage of the device. Such profiles come from real measurements and are applicable for the devices (or group of devices) that have stable and well-defined work cycles. Examples are a dishwasher, a fridge or a freezer. Profiles are also reliable when there are many small consumers of energy, for example light bulbs. In this case a single device has little influence on the overall power consumption and multiple small deviations tend to level the usage.

Profiles define the average, typical behavior and are not suitable to describe events that happen with low frequency or occurrences of extreme power usage. For example, the profile of a coffee machine is repeatable and can be measured, but the information of how often and when users make coffees has to be derived from statistical behavior. Representing small variability in the generated data is troublesome in simulators based on profiles, particularly when random disturbances are introduced.

One solution is to define multiple profiles for a single device, in order to increase the diversity of generated data; there might for instance be 10 profiles for a computer. It can be switched on for 1 hour or for 24 hours, might be used for energy demanding calculations or might be in a sleep mode for most of the time. This approach would require a large number of different profiles that would represent certain cases and still only allow for a limited number of possible combinations.

Each device in the microgrid is connected to the node of the network. Nodes group devices according to their function and location in the building. These profiles were used for calculations of power flow in the network and to calculate possible violation of power constraints in the initial stage of designing the grid. The power consuming nodes were initially divided to general 17 categories:

- air condition in the rooms (1)
- ventilation in the rooms (2)
- preparation of the meals (3)
- powering of the elevators (4)
- external lighting of the buildings (5)
- interior lighting of the buildings (6)
- teleinformatic equipment of the buildings (7)
- other consumers (8)
- power feed of boilers (9)
- power feed of circulation pumps (10)
- power feed of cafe equipment (11)
- power feed of hydrophore (12)
- power feed of waste water pumps (13)
- power feed of meteorological station (14)
- power feed of heat pumps(15)
- power feed of the buildings (16)
- power feed of science experiments (17)

During development of the system new categories were added:

- power feed by single hotel room (20)
- power feed by double hotel room (21)
- power feed by empty hotel room (22)

The categories have daily profiles, connects the percentage of power use by the node with time of the day; an example of the profiles are presented in Fig. 3.27.

The list of categories was made for the defined system, but it can be easily expanded if needed. General profiles are useful when considered very regular power feeds or ones that are a sum of power feed of devices that require relatively small power, like for example light bulbs. That is why for generation profiles are used for such categories as heat pumps, meteorological station or lighting. Categories like other consumers or preparation of meals are too general to be fully useful. The main limitation of the profiles is that they have defined one value per hour, which is not frequently enough if the quasi real time processing is considered. Also lack of information about the variance within the hour period makes it difficult to add some randomization in the profile.

Using of the profile is very simple, the algorithm just chooses the proper value from the profile based on hour of the day, adds some small value to randomize the power usage and returns the usage.

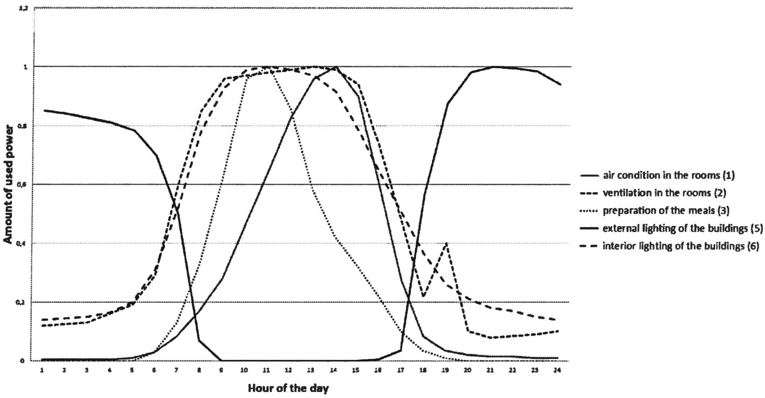


Figure 3.27: Examples of profiles for chosen categories of devices.

Probability profiles Profiles are very suitable and adequate to represent devices which are dependent on time of the day (e.g. light, ventilation). When a device shows a big variance in the operating time, profiles become imprecise and not useful. The main example for device that cannot be described by the profile is a computer: it is a device that if once switched on usually stays on for a long time, even when it is not used. This is due to long start up and shutdown time; the long time needed of starting and closing programs that are needed during work; and the false assumption that the components of the computer get used more quickly during the switch on and off phase [4]. When computer is not occupied by the tasks it can enter an idle mode, in which it uses around one third of the average power consumption. Users tend to switch on the computer when they come to work and switch it off in the afternoon when they go home, but some group of people would schedule time consuming operations for night time and then do not switch computer at all. During short brakes at work, people often do not bother to switch off the monitor or printer, let alone the computer.

For such devices, some other way of describing power consumption had to be defined. Here, We propose describing a device using probability profiles: in this case the profile is not showing the total power consumption at certain time of the day, but the probability of switching the device on and off. For each case of device at least two profiles are needed: one for switching on the device and one for switching it off. Example of the profiles for a device is presented in Fig. 3.28, it shows that at 4 pm this device can be switched on with 5% probability (if at the time it is inactive) and will be switched off with 20% probability (if it is active).

There might be multiple profiles for a single type of device representing different possible behaviors, but each device has to have one pair for probability profiles (if it is described using this category). In the beginning, the program reads the profiles from database, then calculates which part of the profile apply to the current time (in general situation profile can be defined for periods of time shorter than 1 hour). Then, a random value is generated and, depending of the state of the device, this value is compared to the value of probability of switching on or off of the device. If the device is on and stays on, the value of it energy consumption is changed by adding or subtracting some value from the last state (or average state if the device was just switched on), this value takes values from Gaussian distribution.

The example of the output of a consumption generator for one chosen node is presented

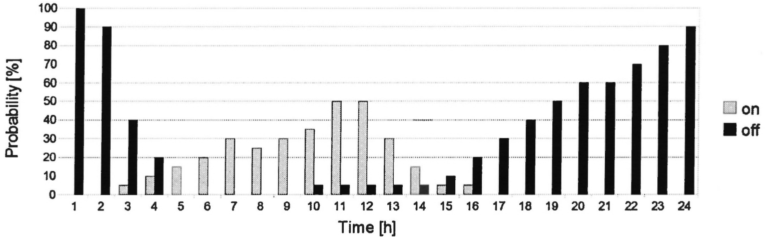


Figure 3.28: Examples of probability profiles for switching on and off of the device.

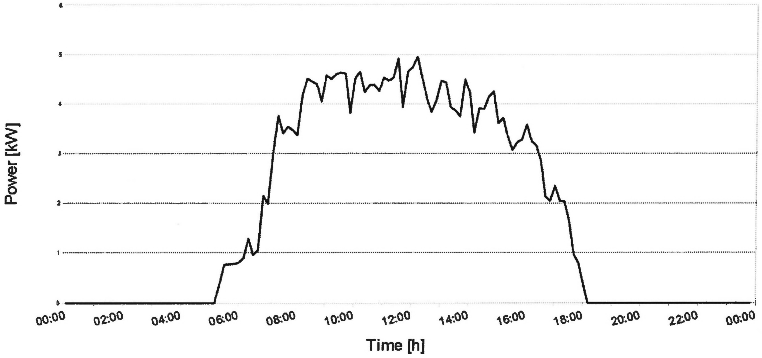


Figure 3.29: Examples of probability profiles for node 189.

in Fig. 3.29. It is the node that has 12 computers and one projector connected to node 189. Each computer is defined by 5 pairs of probability profiles, the consumption of projector is defined by a rule as considered in the next paragraph.

Rules The power consumption of devices that do not have typical profiles and are not working for long time have to be described differently. An example of such a device is a microwave: it is switched on for short moments, maximum few times a day, usually in the afternoon or evening. The method of describing that behavior may be a probability distribution of switching on the device. That means describing loads by a set of rules. The difference with probability profiles is that here the device works a few times per day, for a short or fixed period of time, with the rule defining when it starts operation. This type of description is introduced in [1] according to the Spanish behavioral data. The work of appliances like dishwashers, ovens, etc. is described by the probability of their operating in a certain time. For example, an electric kitchen (a stove) is mainly used around 9:00, 13:00, and 21:00 hours with the respective probability around 2% at the 9 o'clock, 10% at the 13 o'clock, and 20% at 21 o'clock [1](page 100). To simulate the consumption data, some random generators have to be used to ensure that each generation will be different, but that the average operation time is within some defined limits. The user has to be able to define for instance that the microwave operates by average twice a day somewhere between 10:00 to 16:00 and on average it is heating up food for 2 minutes.

This type of description might be giving large variability in consumption generation, but this is the expected behavior. Obtaining such rules require detailed studies on a large enough sample, which is difficult and costly to conduct. The advantage of using such approach is that, by increasing the certainty of the behavior, the rule can be easily adjusted .

A rule is defined by the set of parameters:

- duration – a value describing the average duration of the active period of given device,
- time from – earliest time of the day that the device can start working,
- time to – latest time of the day that the device should stop working,
- amount – amount of power that device uses during the activity period,
- number of times – a value describe how many times the device is active in a given time frame,
- deviation of time – deviation of the switch on time of the device,
- deviation of amount – deviation of the amount of power the device use,
- deviation of duration – deviation of the length of the active time of the device,
- deviation of number of times – deviation of the number of times the device is switched on during given time frame.

An example of the simulation using rules is presented in Fig. 3.30, which shows a node to which four projectors are connected. They are defined using the same rule:

- duration:120 [min];
- time from:09:00:00,
- time to:17:00:00,
- amount:0.1,
- number of times:5,
- deviation of time:20 [min],
- deviation of amount:0.1,
- deviation of duration:20[min],
- deviation of number of times:2.

Note that the term rule includes the random aspects: two devices that have the same rule may have a different operation profile in the simulation. The values for the presented example are input arbitrary, as unfortunately no research has yet been made about the frequency of using the projectors.

The algorithm of generating such data has one major complication: a device might be switched on multiple times, but the periods of switching on should not overlap. In this example we would like that projector is switched on for two hours, we can imagine the situation when it has to be on for 240 min, or 250 min, but we would not like to see it on for 30 minutes. That is why we prefer that the time periods in which the projector is switched on are not overlapping. To realize that requirement, the algorithm uses a heuristic algorithm of choosing the time period, the time period when the device is active

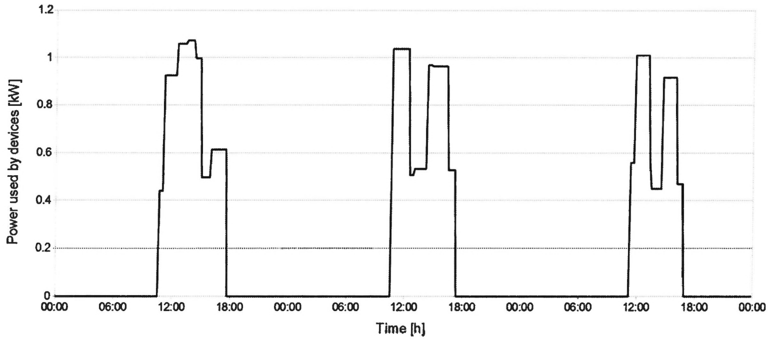


Figure 3.30: Examples of simulated power consumption for node 124.

is called activation period. The outline of the algorithm of simulating the devices power consumption from the rule is presented in Alg. 1. The most interesting part of it is the function correctOverlap, which is in more detail shown in Alg. 2. The method iterates through all the set activation periods and checks for overlaps, if the overlap is found it randomly chooses if the chosen time should be shifted backward in time or forward. Shifting means moving the chosen start time of the device in such a way that it starts immediately after the overlapping activation period (in case of forward shift) or that it ends immediately before the activation period starts (in case of backward shift). The trick is that each time the shift is made, the activation period counter is resetted to initial value, which forces the program to check from the beginning for overlaps. This algorithm uses random shifting and is not guaranteed to simulate the requested number of activation periods, but it prevents overlap and does not distribute the activation periods which would look artificial.

Algorithm 1 ruleGenerate()

```
Create empty profile
Find rule for this device
Draw number that indicates how many operation cycles has the device
for $i = 0$ ; $i < numberOfTimes$ ; $i++$ do
    duration =chooseDuration()
    chosentime = chooseTime()
    chosentime = correctOverlap()
    addToProfile(duration, chosentime)
end for
```

Combined rules with short profiles The above methods suit most categories of devices, but there can still be devices that don't fit in one of these three patterns. The combination of rules with profiles allows for such devices: devices that are switched on at some point in time (defined by the rules), but then show a more complex power profile (defined by the profile). An example of such a device could be a dishwasher, which, dependent of the cycle has a different consumption. An example such a description for devices connected to one node is presented in Fig. 3.25. For devices described by a profile, such as a fridge or a freezer, the profile is used. Devices that are activated by a person and

Algorithm 2 correctOverlap()

```
counter =0
for $j = 0 ; j < i ; j++$ do
    if counter>n then
        return null; {It is not possible to find time period when device will be switched on.}
    end if

    if chosentime overlaps with previously chosen operation times then
        if randomBoolean == true then
            chosentime = ShiftForward()
            if chosentime outside of the time limits then
                chosentime = ShiftBackward()
            end if
        else
            chosentime = ShiftBackward()
            if chosentime outside of the time limits then
                chosentime = ShiftForward()
            end if
        end if
        counter++; j=-1;
    end if
end for
return chosentime
```

controlled by person's actions, are described by rules. Devices that would benefit from both are appliances that are operated by a person, but if they are switched on they have some fixed operation cycle. An example of such situation is a dishwasher: the user chooses the time to switch it on, but the cycle is almost the same. The rules define a probability of starting an action at certain time. When a device is active, the simulator generates consumption data according to its profile. A rule has the same set of parameters as in section 3.4.3.

Profiles are by default short and unlike the rules from section 3.4.3, they are described as a list of pairs: minute of change and value. The minutes represent a moment of change: the first minute is always 0 and the next entry is showing how many minutes later the change in power occurs. The value represents the percentage of the maximum power usage of the device to which it will be switched. An example of the generated profile for node 152 is presented in Fig. 3.31; this node has 4 printers connected, each of which has defined rules and profiles.

3.5 Conclusions and further work

The research considered in the project spans many different problems: from scheduling to energy trading. The work presented aimed to create a complete simulation of the research and education center. Coping with the real microgrid project is challenging and shows how many simplifications had to be made due to lack of knowledge how real system would work. The main framework for energy management has been presented, as well as the framework for simulating the power generation and consumption of the research center. There still is the aspect of describing and modelling the behavior of people working in such a center, but more data is needed before this can be put into the framework. Many improvements are

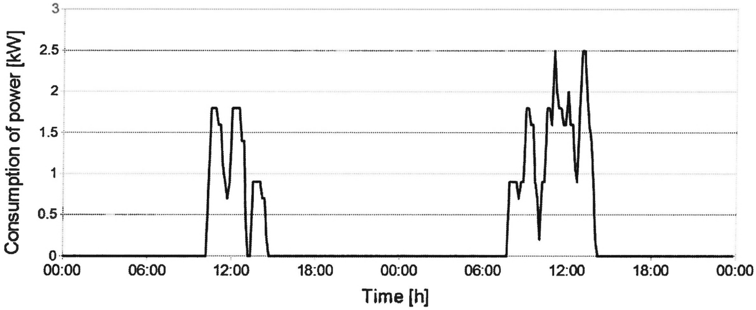


Figure 3.31: Examples of simulated power consumption for node 152.

still possible in many subsystems (Planner, Short-time power balancing, energy trading module, etc.), but the current work already indicates that an EMS can be designed to manage power in a microgird and that it can help to introduce more ecologically oriented and cheaper solutions.

But before real-life microgrids appear, there can still be many improvements in theoretical approach and in simulation. The problem considered in Planner – scheduling of operation is a complicated problem solved using heuristic algorithms, still has some unsolved issues. The question raises which events can be controlled, and to what extent.

If the constraints provided by the users are very strict, the scheduling algorithm has not much freedom to change or suggests times, which negates the usefulness of the complicated mechanism. Finding the optimal balance between the limitations of control and the possible concession people are willing to make still needs to be checked. Part of this is of course more psychological and behavioral research. If on the other hand the constraints provided by the users are not strict, the scheduler has much more freedom and more efficient scheduling algorithms (perhaps including rescheduling) are interesting topics for future research.

The subsystem for short-time energy balancing is an attempt to deal with ultra short-time changes by using a computer system. The next chapter, and chapter 5 deal with the abstraction and implementation of the subsystem. This subsystem is a critical component, and for proper operation of the microgrid an uninterrupted operation for longer duration is expected, while handling everything in real time.

Energy trading is a very hot topic as the energy markets were opened not long time ago [70] and are still under subsequent development in many countries. Challenges with new technologies give incentives to redefine the power electricity market, e.g. in [43] authors suggest treating electric energy markets as the multicommodity markets. Due to the specific properties of energy (partly explained in chapter 2) the energy will always have to be transferred and traded, more research is needed to make this trading fair, profitable, reliable and resistant to different types of collusions.

The generators were created with the aim of being fast and using available data. The generation of supply side is very widely researched, there are a number of models based on wavelengths [124], time series [129] and others. The most problematic out of all natural forces is the irradiance. Irradiance, when treated as time series, presents long periods of zeros with very well defined cycles, but the cloud coverage is not modeled enough and poses a difficulty for forecasting and simulation.

There are vast studies including modeling of water level in the rivers, e.g [58]. But most of the studies consider big rivers, that carry a lot of water and the effect of very sudden water level changes does not apply. In our case, more sophisticated models for small rivers should be applied.

The generation of demand site is much more difficult and to some point research is lacking. There is a lot of work on Demand Side Management, but they usually consider households and work more on shifting and controlling and less on how people use equipment. The measurements are done at small, chosen groups that have reasons and incentives to take part in such program; there is a question how representative they are. The demand side management is an interesting concept that was not considered in this work – just the generation of demand. The description of demand is complicated and case based. It was made to be easily editable and stored in database, for easier reproduction of experiments. In a microgrid environment, small changes in load have a big impact on overall balance. To have statistically significant data about microgrid operation, a large number of long-term tests has to be made. A real infrastructure for testing purposes is often not available. Detailed profiles of energy usage of devices can be measured, but they do not reflect the way people use devices. User behavior is very varied and influenced by many factors. The simulator of energy consumption has to mimic this behavior with all its impreciseness and unpredictabilities, for which we used probabilistic distribution combined with fixed profiles. The presented energy consumption simulator requires rules and profiles that define device's behavior. Based on that, a time series of energy consumption aggregated per node is created, which is a tool for EMS testing.

Energy management systems deal with all type of energy sources and power consuming devices. Many of them have certain work cycles, which depend on the time of the year, the day of a week, or the hour of a day. The described weather conditions generator provides data that include randomness and can produce series of any length. The advantage of this method is its simplicity, fast computation and good statistical properties. The main disadvantage is its high dependence on the amount of available measured data and their representativeness.