THE DEVELOPMENT OF ACTIVE DEMAND SIDE MANAGEMENT FOR ENERGY UNITS

DOCTORAL THESIS

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DOCTORAL THESIS

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Statutory declaration

I hereby declare, that this doctoral thesis has been written by myself and all used references are cited in the references list.

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In Ostrava, Czech Republic, 2015

Jindřich Stuchlý
## Nomenclature

<table>
<thead>
<tr>
<th>Abbreviations</th>
<th>Description</th>
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<tbody>
<tr>
<td>AC</td>
<td>Alternating Current</td>
</tr>
<tr>
<td>ADSM</td>
<td>Active Demand Side Management</td>
</tr>
<tr>
<td>AEU</td>
<td>Active Energy Unit</td>
</tr>
<tr>
<td>DAQ</td>
<td>Data acquisition</td>
</tr>
<tr>
<td>DC</td>
<td>Direct Current</td>
</tr>
<tr>
<td>DESs</td>
<td>Distributed Energy Sources</td>
</tr>
<tr>
<td>DG</td>
<td>Distributed Generation</td>
</tr>
<tr>
<td>DLC</td>
<td>Daily Load Curve</td>
</tr>
<tr>
<td>DOD</td>
<td>Battery bank Depth of Discharge</td>
</tr>
<tr>
<td>DSM</td>
<td>Demand Side Management</td>
</tr>
<tr>
<td>ICT</td>
<td>Information and Communication Technology</td>
</tr>
<tr>
<td>LPG</td>
<td>Liquefied Petroleum Gas</td>
</tr>
<tr>
<td>LV network</td>
<td>Low Voltage network</td>
</tr>
<tr>
<td>MV network</td>
<td>Medium Voltage network</td>
</tr>
<tr>
<td>NG</td>
<td>Natural Gas</td>
</tr>
<tr>
<td>PC</td>
<td>Personal Computer</td>
</tr>
<tr>
<td>PV</td>
<td>Photovoltaic</td>
</tr>
<tr>
<td>RES</td>
<td>Renewable energy source</td>
</tr>
<tr>
<td>RLC elements</td>
<td>Resistance, Inductance, Capacitance element</td>
</tr>
<tr>
<td>SoC</td>
<td>Battery bank state of charge</td>
</tr>
<tr>
<td>VI</td>
<td>Virtual Instrument</td>
</tr>
<tr>
<td>VŠB-TU Ostrava</td>
<td>Vysoká škola báňská – Technická univerzita Ostrava</td>
</tr>
<tr>
<td>XML</td>
<td>Extensible Mark-up Language</td>
</tr>
<tr>
<td>WPP</td>
<td>Wind power plant</td>
</tr>
<tr>
<td>Yr</td>
<td>Year</td>
</tr>
</tbody>
</table>
Abstract

This doctoral thesis presents a heuristic approach to Active Demand Side Management (hereinafter ADSM) in the Off-Grid systems with a set of specific requirements, while the requirements are the same like in the Smart-Grids. This doctoral thesis introduces develop, test and analyse the concept of the sophisticated automated dispatcher system of family house power level. The tests were performed on the smart house platform developed at the campus of VŠB - Technical university of Ostrava, Czech Republic in order to accomplish the effective design, testing, operation and analysis of the proposed system. These results consequently consist of a perquisite for the development of new leading-edge power distribution system in the Off-Grid environment and for improvement of the efficiency, security and reliability of the existing systems. Moreover, the results are scalable, and then applicable to the different energy levels, such as Smart house communities, Smart cities, Smart-Grid regions or can also help with electrification in rural or island application in developing countries. This doctoral thesis deals with the physical platform of Active energy unit as a hardware part and ADSM as a software part of the system, next Techno-Economic Analysis is carried out and practical experiments are evaluated. Scientific contributions, added value and benefits of proposed ADSM are summarized in conclusion.

Keywords
Active Demand Side Management, Off-Grid System, Artificial Intelligence Techniques, Active Energy Unit, Renewable Energy Sources
1. INTRODUCTION & MOTIVATION

At present time, electricity is an integral part of human society. The electrical energy dependency has increased with a rising standard of living in the developed countries. The major part of the electric energy production is formed by the combustion of coal, oil and natural gas together with the energy obtained from the atom’s core using fission reactions, radioactive decay and thermonuclear fusion. Renewable energy sources of electricity (RES), such as wind power plants (WPP) and photovoltaic power plants (PV) have been used as an alternative to fossil non-renewable resources [1].

These ecological sources of electrical energy in the case of power supplying to the distribution system have for the distribution and transmission systems operator a several negative effects due to their stochastic character, non-continuous of power supplying to the connection point. These negative effects significantly jeopardize the reliability and stability of the distribution network [2], [P4] - [P9].

One of the ways how to make maximum use of the potential and minimize the negative effects of renewable energy sources is the local consumption of generated energy, e.g. in the power closed system, such as in Smart-Grids. The Smart-Grid can be regarded as an electric system that uses information, two-way, cyber-secure communication technologies, and artificial intelligence across electricity generation, transmission, substations, distribution and consumption to achieve the system, which is clean, safe, secure, reliable, durable, efficient, and sustainable. In the recent years, the development of the Smart-Grid technology has been posed as one of the greatest achievement in the power sector, due to deployment of RESs and the application of sophisticated control algorithms on the power converters for grid interconnection [3] - [5], [P11].

In case of the Smart-Grid system, that is district distribution grid with possibility of autonomous running in an island-mode (Off-Grid) and running in parallel with an external distribution system (On-Grid). The Smart-Grid is an evolved grid system that manages electricity demand in a sustainable, reliable and economic manner, built on advanced infrastructure and tuned to facilitate the integration of all involved. The Smart-Grids possess demand response capacity to help balance electrical consumption with supply, as well as the potential to integrate new technologies to enable energy storage devices and the large-scale use of electric vehicles [6], [P21].
The basic block scheme of a typical Smart-Grid is shown in Fig. 1 and consists of several basic elements: power sources, power consumption and transmission elements, where co-generation unit takes care about the medium voltage (MV) network parameters and creates the backbone of Smart-Grid voltage network together with (Low Voltage) LV / MV network transformers allowing bi-directional power flows. Another part of Smart-Grid are RESs (e.g. PV and WPP). Consumption parts create office buildings, households and industrial objects. The energy storage system or superior (external) power grid can cover the actual consumption in the time of a lack of energy.

PVs and WPPs are used as an addition for the electric energy generating according to meteorological and geomorphologic condition in specific place of Smart-Grid.

There are several tools which are needed in order to obtain the benefits we envision from Smart-Grids. To deserve the attribute “Smart”, the grid has to be operated under a specific set of requirements, namely:
I. Autonomous operation without a dependence on energy from external power grids,

II. Operation with an equable generation-consumption balance,

III. Possibility of energy storage,

IV. Predominant use of RESs,

V. Capability to serve non-traditional loads,

VI. New type of grid protection allowing for a bi-directional power flow, and

VII. The Active Demand Side Management [7] - [13], [P1].

Due to the stochastic nature of RESs, one of the key problems associated with the RESs is that the time period in which the RESs produce energy often does not coincide with the period when the energy is demanded. There are many concerns about the flexibility, variability, non-controllability of these sources, and they have an impact on the ability maintain the power balance between supply and demand [7]. We usually manage the demand side to help balance the supply. Currently, we use the set of supply-side generation reserves, known as ancillary services, to regulate the supply-demand mismatch. However, rapidly increasing of penetration of RESs decreases the controllability of the supply side. The rise in the needed balancing power can be managed by utilizing the flexibility potential in demand and energy storage along with RESs so-called, Distributed Generation (DG) [8]. The introduction of Distributed Energy Resources (DERs) (e.g. household, industrial consumers and electric vehicles with energy storage), together with the introduction of additional Information and Communication Technology (ICT) in the electricity system provides interesting and novel automated Demand Side Management (DSM) opportunities at the end user level.

The goal of the “standard” DSM is to encourage the consumer to use less energy during peak hours, or to move the time of energy use to off-peak times such as night-time and weekends. Peak demand management does not necessarily decrease total energy consumption, but could be expected to reduce the need for investments in networks and/or power plants for meeting peak demands. An example is the use of energy storage units to store energy during off-peak hours and discharge them during peak hours [14], [15].

The combination of DSM with the automatic control of the DERs demand can be called “Active Demand Side Management” [16], [P1]. ADSM can modify the demand profile to reduce the losses
in the grid, maximize consumption while RESs are available, decrease congestions, and save energy. ADSM uses forecasting models based on artificial intelligence techniques for power generation from RESs such as WPP [17] and PV [18]. The system also uses the power consumption forecasting model for different types of consumers, power quality forecasting tool [P14] and implements new adaptive protection systems [P2], [P13], [P26]. The main benefit of this active management system is to make the Off-Grid system independent from the external power grid for year-round operations, improve the comfort of the living as well as reduce and optimize the power consumptions or decrease the price of installation with cheaper/smaller batteries or smaller power plants, and maximize consumption when production from RESs is the highest [3], [4].

Another extremely important goal of ADSM is hidden in the word “ACTIVE” in the title. The “ACTIVE” means, that the users can change the priority of the appliances based on their own ideas regarding living comfort as well as the possibility of the dynamic changes in the individual appliances time scheduling over time. The primary goal of the ADSM is to meet the basic requirements of house inhabitants, such as keeping food fresh, food reheating and cooking, thermal comfort, etc. The benefits of ADSM can also be achieved with different techniques, such as peak clipping, valley filling, strategic conservation, strategic load growth, load shifting, flexible load shape, direct load control, frequency regulation, etc. [19].

From my point of view, the proposed Off-Grid system operated under the ADSM could be considered the basic cell of the entire Smart-Grid system, because households, office and industrial buildings make up the energy consumption backbone of the Grid. The Off-Grid systems can be operated in a true autonomous mode, but also as a semi-autonomous unit – with external grid interaction. The semi-autonomous operation would be the basic solution for the Smart-Grid, because these intelligent power networks will make use of the de-synchronization and resynchronization of part of the network up to an individual energy object in order to maintain an equitable generation-consumption balance, blackouts avoiding, etc. [20]. This doctoral thesis presents, however, analysis and experimental work in an Off-Grid area with the primary goal being to make the Off-Grid system independent from the external power grid for year-round operations, when the grid interaction is not considered – pure Off-Grid system operations.
As a testing platform has been selected the (family house) household platform developed on a university campus, because it allows for effective testing and makes the necessary changes in HW or SW parts extremely promptly.

The potential scalability of the system lies in the changing of the system inputs and outputs (power sources, loads, energy storage system, etc.), while the next project where I participate is to operate an industrial building – the Automated Traffic Centre at the university campus (multilevel car parking), as an Off-Grid system operated under the ADSM. The planned aim is to create a Smart-Campus, which is in fact, Smart-Grid community.

The utilizing of the ADSM with RESs and energy storage systems can also help with electrification in rural or island applications in developing countries [21] - [25] or for humanitarian aid [26].

With regard to the results of the available research in the literature it should be noted that most of the research works deals with the issue of controlling the power flows using ADSM or only DSM not in a comprehensive and all-purpose meaning.

In Ref. [12], the authors used the DSM and optimal energy consumption strategy to minimize the peak load by transferring a suitable load to off-peak hours. In Ref. [27], the authors have focused on the Smart Home Controller strategy to determine the best time to run the smart household appliance and take into account the actual power threshold and consumption forecasts. The method described in [28] presents the results of classifying the load curve patterns to choose the most suitable DSM policies for each type of consumers using the artificial neural network tool. In Ref. [29], an innovative method to manage the appliances on a house during a demand response event has been proposed. Nevertheless, the results presented in [27] - [30] do not take into account that the RES are implemented in these kind of systems. In contrast, in [31], the authors have proposed the ADSM in the terms of using artificial intelligence techniques tuned by a genetic algorithm implemented in an actual operated system with a battery bank and installed PV, however, the authors only solved the maximization of the self-consumption in the residential sector and did not solve the case of a lack of the energy in the object over the long term. There are also publications [32], [33] and [34] which discuss the general approach, future development and trends for DSMs, micro-grid and Smart-Grids.
To be precise, the proposed research work in this doctoral thesis involves developing a novel method and approach for ADSM in Off-Grid system operated in a Smart-Grid environment. The proposed method combines artificial intelligence techniques along with deterministic algorithms in cooperation with software and hardware parts to complete the Active Energy Unit (AEU) [P27].

Off-Grid system operated under the proposed ADSM can significantly reduce the power outage as a result of intelligent scheduling. The tests are performed on the smart house platform developed at VŠB – Technical University of Ostrava campus, Czech Republic to accomplish the effective design, testing, operations and analysis of the proposed system. Furthermore, the simulations results are presented here based on practical experiments with AEU platform operation and computer simulations with actual weather conditions, power consumptions, etc. The proposed ADSM demonstrates the ability to intelligently spread out the energy requirements over the day in order to achieve the maximum living comfort while energy independence is guaranteed.
1.1. Objectives of doctoral thesis

This doctoral thesis is elaborated in accordance with the accepted thesis of the state doctoral examination and the objective of doctoral thesis is the development of Active Demand Side Management for Energy units.

The Active Demand Side Management is understood as a sophisticated automated dispatcher control system which is able to control the power flows inside any energy unit based on input information. Specific properties of the AEU include energy independence, prioritizing of appliances, and implementation of forecasting tools or applying of innovative solutions.

The individual phases of solution can be summarized in following points:

I. Phase – The development of Active energy unit testing platform
   - Design and realization of source part
   - Design and realization of part of energy conversion and transfer
   - Design and realization of energy storage device
   - Design and realization of energy consumption part
   - Measure and control system

II. Phase – The Active Demand Side Management
   - Correlation analysis
   - The development of Active Demand Side Management
   - Testing, implementation and validation of developed Active Demand Side Management
2. DESCRIPTION OF THE PHYSICAL PLATFORM OF THE OFF-GRID SYSTEM

This chapter describes the each component of the AEU platform in details in accordance with the accepted thesis of the state doctoral examination (I. Phase).

The term Off-Grid is currently extremely widespread topic and has several meanings. It is a lifestyle, when people try to separate from the conventional way of life and be in harmony with nature, simply said “Off the Grid”. On the other hand, it is about energy independence on the distribution network, because of the financial costs associated with the construction of the electrical connections or the impossibility of this electrical connection.

The Off-Grid systems are usually composed of hybrid renewable energy sources, more precisely wind and photovoltaic power plants, which are supplemented by a backup source of electrical energy in the form of power generators for various kinds of fuel – gasoline, natural gas (NG), Liquefied Petroleum Gas (LPG), diesel, etc. In order to ensure the continuity of supply of electricity at all time, it is necessary to add a source where can be the energy stored in the time of low energy demand and cover the energy peak, when needed. In autonomous applications are most commonly used Lead-Acid, Nickel-Cadmium and Lithium-based batteries [P12], [P18].

The developed physical platform of the Off-Grid system for intelligent distributed power systems with Active Energy Unit (AEU) at VŠB-Technical University of Ostrava campus is shown in Fig. 2.

The developed system is mainly specified for working in an autonomous mode (Off-Grid) without dependence on energy supplied from an external power grid. This system can also be operated with the cooperation of the external power grid. However, the main goal of this doctoral thesis is to develop the tools and methods which provide the operations of this physical platform in a true Off-Grid mode in the framework of year-round operations. There is an assumed use of an additional power source with the mentioned RESs (PV and WPP) the LPG generator, which uses environmental-friendly fuel - LPG or NG in this true Off-Grid mode.

This platform creates a physical model of AEU, which can be operated under various operating conditions of WPP and PV and various demands of electric power without connecting appliances to the standard AC distribution grid.
AEU physical platform is composed of 2 rooms (laboratories) in one of the buildings (in building “L” – Heavy Laboratories) at the campus of VŠB – TU Ostrava, Czech Republic. The “living” area of these 2 rooms is approximately 50 m². The building can be found at 49°50′00.9″N 18°09′32.0″E. Each room is equipped with a motion detector, light switches, window and door contacts and actuators. It is also composed of RESs such as a wind (WPP in Fig. 2) and PV (PV₁ and PV₂ in Fig. 2) system with a central Off-Grid inverter (CI in Fig. 2), battery bank (BATT in Fig. 2), LPG Generator (LPG/GRID in Fig. 2) and Active Demand Side Management unit (ADSM in Fig. 2), etc. A weather station (WS in Fig. 2) outside the building supplies local environmental measurements of ambient temperature, wind speed, wind direction, relative humidity, atmospheric pressure and solar irradiation. The electrical loads of the building consist of heating, lighting, hot water supply and various household appliances, such as a refrigerator and a coffee machine (Loads in Fig. 2). The combined peak load is close to 20 kW.

At VŠB-TU Ostrava was developed physical model of energy unit, which is able to simulate different operating and fault conditions inside this system, and is capable of respecting the specific requirements of the Smart-Grid as defined above. Physical model consist of several parts:

I. Source part
II. Part of transfer and conversion of electric energy
III. Energy storage part
IV. Consumption part
V. Monitoring system
VI. Control system

2.1. Source part

To create the physical platform of AEU was necessary to design and implement a hybrid power source to a power closed system. The power closed system of consumption is currently made up of several home appliances, office equipment and programmable load. This creates a physical model of AEU where can be simulated various operating conditions of WPP and PV and various
demands of electric power without connecting appliances to the standard AC distribution grid [P19], [P24].

Fig. 2 depicts schematic diagram of used tested platform of AEU. Individual elements will be described in following sub-chapters.

2.1.1. Photovoltaic Power Plant

The Off-Grid system consists of two strings with a total installed power of 4 kWp – 2 kWp each, see Table 1 for details. Fig. 3 shows the power curves for each PV string, the blue curve (PV1) shows the dependency of global radiation of polycrystalline panels installed on the roof of the building and the red curve (PV2) monocristalline panels installed on the tracker, see Fig. 4 for PV’s situated in the university campus.
Based on Fig. 3, it should be noticed that the power output from the 1st string of the PV panel almost linearly increases with solar irradiation whereas the power output from the 2nd string of the PV panel precisely follows the solar tracker throughout the day and maximum possible energy is extracted from it.

PV1 is composed of 12 PV panels under angle about 15°, where 6 PV panels have eastern and 6 PV panels have western orientation. PV2 consists of 12 panels that are installed on a two-axial pointing device, so-called tracker which uses the control electronics to achieve the PV panel’s ideal angle and orientation to ensure maximum profits of electric energy throughout the day.

The tracker is able to increase the power production up to 30% in direct comparison with the permanent installation. The power consumption absorbed by the tracker for the self-consumption has been taken into account in this value. This argument is well-founded by using the database of measured values. The control unit allows maximum use of sunlight (even on cloudy days). Tracker uses to follow the sun linear motor and harmonic gearbox, which are controlled by control electronics.
Table 1 PV’s parameters

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Value</th>
<th>PV1</th>
<th>PV2</th>
</tr>
</thead>
<tbody>
<tr>
<td>PV cell technology</td>
<td>-</td>
<td>Polycrystalline</td>
<td>Monocrystalline</td>
</tr>
<tr>
<td>PV Area</td>
<td>m²</td>
<td>19.5</td>
<td>19.2</td>
</tr>
<tr>
<td>Maximum power</td>
<td>W</td>
<td>2,220</td>
<td>2,160</td>
</tr>
<tr>
<td>Voltage at maximum power</td>
<td>V</td>
<td>29.8</td>
<td>36.0</td>
</tr>
<tr>
<td>Current at maximum power</td>
<td>A</td>
<td>6.2</td>
<td>5.0</td>
</tr>
<tr>
<td>Short circuit current</td>
<td>A</td>
<td>8.34</td>
<td>5.2</td>
</tr>
<tr>
<td>Open circuit voltage</td>
<td>V</td>
<td>36.8</td>
<td>45.0</td>
</tr>
</tbody>
</table>

*Fig. 4 PV1 and PV2 at the University Campus*

2.1.1. Wind Power Plant

The source with the biggest installed power is wind power plant with active power of 8 kW. It is the wind power plant with three phase 20poles synchronous generator with permanent magnets (PMSG). WPP is equipped with a control system that operates automatically, when the wind speed exceeds the pre-set wind speed limits. The nacelle deviates from wind direction (relative angle of 30°, 60°, 90°), to not exceed the limit system parameters. See Fig. 5 for WPP in university campus.
WPP is able to operate in two modes, while 1st is On-grid and 2nd is Off-Grid operation mode. See Fig. 6 for developed algorithm for automatic switching between Off-Grid and On-Grid mode.

The default operations mode for proposed algorithm is the Off-Grid mode. The 1st operation mode of WPP is power supply to Off-Grid system. Variable AC voltage of generator (0 – 425 V/0 – 35 Hz) is rectified with three phase rectifiers to DC voltage. Subsequently, the DC voltage is applied to a one single phase inverter. Another task of the rectifier is to protect the inverter from excess generator’s voltage by feeding excess to a load resistor. In this mode is whole electric power of WPP supplied to one inverter, because WPP usually works below 40 % of installed power. During a windy day or under conditions presented in Fig. 6, is WPP switching from 1st to 2nd operation mode and it allows the WPP works up to 100 % of the installed power.
The 2nd operation mode is public grid operation into three phase distribution system (On-Grid). Connection method is similar to the previous mode. Variable AC Generator’s voltage is applied to two three phase rectifier; rectified DC voltage is applied to three single phase inverter that supplies the On-Grid system – distribution system. Three single phase inverters are superimposed to three phase distribution system from certain voltage level in DC link (250 V DC). Dynamics of wind turbine operation causes rapid changes in energy in the DC link. Inverters require some times to start their activities, so in this time is the energy thwarted into load resistor (dump load) to protect inverters for overvoltage.
Description of the physical platform of the Off-Grid system

Fig. 7 WPP power curve

Fig. 7 depicts the WPP power curve. This power curve has been compiled from monitoring system (detailed description in section 2.5) for On-Grid mode, because in Off-Grid mode are different conditions in comparison with On-Grid mode. Based on the manufacturer declaration, the rated power of the WPP should be ca. 12 kW, however the measured data show that the power at rated wind speed (12 m·s$^{-1}$) is about 8 kW.

Table 2 Wind power plants parameters

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Unit</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Generator type</td>
<td>-</td>
<td>Synchronous with permanent magnets</td>
</tr>
<tr>
<td>Manufacturer</td>
<td>-</td>
<td>AER Plast s. r. o.</td>
</tr>
<tr>
<td>Installed power</td>
<td>kW</td>
<td>8</td>
</tr>
<tr>
<td>Maximum AC voltage</td>
<td>V</td>
<td>425</td>
</tr>
<tr>
<td>Nominal/Maximal wind speed</td>
<td>m·s$^{-1}$</td>
<td>12/50</td>
</tr>
<tr>
<td>Maximal RPM</td>
<td>r·min$^{-1}$</td>
<td>180</td>
</tr>
</tbody>
</table>
2.1.1. LPG Generator

The installed LPG generator is a suitable additional power source in Off-Grid systems. The purpose of the LPG generator is power supply for the most important appliances when other sources (PV and WPP) and the powerless and battery bank is discharged. Another purpose, equally important as the previous one, is the maintenance of the energy storage device, because the battery bank used in the Off-Grid system has to be fully charged occasionally to maintain the battery bank capacity, lifespan, etc.

![Generator's AC Frequency (Hz) vs. Generator's Output Voltage (V)](image)  
*Fig. 8 Voltage and frequency characteristics of the LPG Generator*

Fundamental parameters of power frequency (global parameter) and voltage (the local parameter) are in any AC electricity grid or in general at the source of electrical energy. Fig. 3 depicts that this LPG Generator of electrical energy behaves like a “weak” source, because when the load is changed, voltage and frequency changes occur.

The LPG Generator can use as fuel LPG and NG, which are currently also considered environment-friendly fuel. The installed rated power of the generator is 2.4 kV·A at
230 VAC / 50 Hz. An internal combustion engine drives the 3-phase synchronous generator with permanent magnets.

The generator regulates its voltage to a pre-set nominal voltage using the automatic voltage regulator (AVR) or depending on a characteristic curve. The generator’s behaviour (synchronous generator) must be observed depending on the generated or absorbed reactive power (voltage increase with the leading load). This distributes the reactive power between the sources connected in parallel during the operations. The voltage is regulated at the generator by varying the excitation voltage. It allows the voltage to be quickly regulated at the generator, since there are no mechanical time constants to consider here. This generally makes it considerably faster than the frequency regulation. The generator’s parameters are summarized in Table 3.

### Table 3 LPG Generator parameters

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Engine type</td>
<td>OHV, four-stroke single-cylinder</td>
</tr>
<tr>
<td>Generator type</td>
<td>Synchronous Generator with AVR</td>
</tr>
<tr>
<td>Cylinder displacement</td>
<td>389ccm</td>
</tr>
<tr>
<td>Nominal voltage output</td>
<td>230 V</td>
</tr>
<tr>
<td>Maximal output current</td>
<td>10.4 A</td>
</tr>
<tr>
<td>Maximal output apparent power</td>
<td>2.4 kV·A</td>
</tr>
<tr>
<td>Nominal output frequency</td>
<td>50 Hz</td>
</tr>
<tr>
<td>Fuel consumption at rated load</td>
<td>0.32 kg/kW·h</td>
</tr>
<tr>
<td>Fuel type</td>
<td>LPG/NG</td>
</tr>
<tr>
<td>IP protection class</td>
<td>21</td>
</tr>
<tr>
<td>The sound power level</td>
<td>93 dB (A)</td>
</tr>
</tbody>
</table>

#### 2.2. Part of transfer and conversion of electric energy

Part of the transfer and conversion of electrical energy is an integral part of each system. The hybrid inverter is the most important part of the Off-Grid system. The central Off-Grid inverter is responsible for charging and discharging the batteries and the operations of the entire system using AC coupling topology. The parameters of the central Off-Grid inverter are in Table 4.
Description of the physical platform of the Off-Grid system

Table 4 Hybrid inverter parameters

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rated AC voltage</td>
<td>230 V&lt;sub&gt;AC&lt;/sub&gt;</td>
</tr>
<tr>
<td>Rated AC power</td>
<td>3.3 kW&lt;sub&gt;AC&lt;/sub&gt;</td>
</tr>
<tr>
<td>Rated battery bank voltage</td>
<td>20 – 24 V&lt;sub&gt;DC&lt;/sub&gt;</td>
</tr>
<tr>
<td>Maximal charging battery current</td>
<td>140 A&lt;sub&gt;DC&lt;/sub&gt;</td>
</tr>
<tr>
<td>Maximum efficiency</td>
<td>94.5 %</td>
</tr>
<tr>
<td>Continuous AC output at 25°C for 30 / 5 / 1 min</td>
<td>4.2 / 4.6 / 5.0 kW</td>
</tr>
<tr>
<td>Rated output frequency</td>
<td>50 Hz</td>
</tr>
</tbody>
</table>

The central Off-Grid inverter is capable of making a bidirectional power flow with the help of battery energy storage, inverter and charger, allowing for stable operation of connected loads and power generation devices on the AC side.

The central Off-Grid inverter used in this Off-Grid testing platform creates conditions defined for a standard single phase AC system which can integrate individual electrical appliances. Due to its sophisticated control of the battery bank charging [35] the Off-Grid inverter is always aware of the State of Charge (SoC) of the battery bank and makes further decisions based on its control function in the system. It also determines the optimal strategy for charging the battery bank. If the DC input (battery bank) falls below a predefined limit, the system will shut down automatically. The battery bank charging process uses the IUoU Active Inverter Technology characteristics [36].

Another conversion element in the Off-Grid system is the PV inverter. This inverter has 3 inputs and 2 DC MPPT controllers. PV inverter takes care about superimposing to the Off-Grid network, which creates the hybrid inverter, and constantly monitors the limits of the parameters set in the inverter. An overview of the basic parameters of the PV inverter are summarized the Table 5.
The wind power plant is more complicated power source than the photovoltaic power plant. There is a need to use double-converting elements, because synchronous generators with permanent magnets produce changeable output, in this case $3 \times 0 - 425 \text{ V} / 0 - 35 \text{ Hz}$. The generator’s AC output is first rectified to DC output using rectifier and this output is used as DC input for the inverter. Parameters of these converting elements are shown in Table 6.

### Table 5 PV inverter parameters

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum DC input voltage</td>
<td>$600 \text{ V}_{\text{DC}}$</td>
</tr>
<tr>
<td>Rated DC input power</td>
<td>$4,375 \text{ W}_{\text{DC}}$</td>
</tr>
<tr>
<td>Maximum DC input current / for each MPPT</td>
<td>$32 \text{ A} / 16 \text{ A}$</td>
</tr>
<tr>
<td>Maximum AC output</td>
<td>$4,600 \text{ W}_{\text{AC}}$</td>
</tr>
<tr>
<td>Maximum efficiency</td>
<td>97 %</td>
</tr>
<tr>
<td>Output frequency range</td>
<td>45 - 55 Hz</td>
</tr>
</tbody>
</table>

### Table 6 Wind power plant rectifier & inverter parameters

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Rectifier</th>
<th>Inverter</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum input voltage</td>
<td>$3 \times 440 \text{ V}_{\text{AC}}$</td>
<td>$600 \text{ V}_{\text{DC}}$</td>
</tr>
<tr>
<td>Rated input power</td>
<td>$7,000 \text{ W}_{\text{AC}}$</td>
<td>$6,000 \text{ W}_{\text{DC}}$</td>
</tr>
<tr>
<td>Rated output power</td>
<td>$7,000 \text{ W}_{\text{DC}}$</td>
<td>$5,500 \text{ W}_{\text{AC}}$</td>
</tr>
<tr>
<td>Maximum efficiency</td>
<td>99 %</td>
<td>95 %</td>
</tr>
<tr>
<td>Frequency range</td>
<td>$0 - 400 \text{ Hz}$</td>
<td>$45 - 55 \text{ Hz}$</td>
</tr>
</tbody>
</table>

2.3. Energy storage part

The Nickel Cadmium (Ni-Cd) battery, type: Ferak KPL 375P LM has been used in the Off-Grid system. The nominal battery voltage is 1.2 V and the battery bank capacity is 750 A·h at 24 V DC level. The energy efficiency is about 90 % and the state of charge (SoC) level is set at 40 %, which means ca. 10 kW·h of the available energy in the battery bank is used for power feeding to the Off-Grid system [P12], [P18].

Fig. 9 depicts discharging curve of the Nickel-Cadmium batteries used in the system as energy storage device. The discharge curve was made up of several measurements, in order to minimize
the errors between the actual and measures value using 1000 W programming load on the battery bank. This was found by measuring the quantity of energy in the batteries, this being approx. 10 kW·h at a constant load of 1000 W and a fully charged battery bank. The resulting measured points were approximate, see equation (1) by using a polynomial function, with $R^2 = 0.9984$ (parameter which specifies the precision of the approximation).

$$y = 0.000000008 x^5 - 0.00002 x^4 + 0.0024 x^3 - 0.1701 x^2 + 5.8924 x - 59.596 ,$$  \hspace{1cm} (1)

where $y$ is the battery capacity (W·h) and $x$ is the battery bank voltage ($V_{DC}$).

**Fig. 9 Ni – Cd battery bank discharging curve**

### 2.4. Consumption part

Part of the electricity consumption in the Off-Grid system has significant effect on the parameters of installed power sources, such as PV, WPP, LPG Generator and battery bank or e.g. the power quality parameters of electric energy [P24], [P19]. The electrical appliances used in the proposed Off-Grid autonomous energy unit are household appliances, office equipment and programmable load and are summarized in the following Table 7.
Table 7 Electrical appliances used in the physical platform of AEU

<table>
<thead>
<tr>
<th>Appliance</th>
<th>Amount (pcs.)</th>
<th>Power input (W)</th>
<th>Power Factor (-) R, L, C</th>
</tr>
</thead>
<tbody>
<tr>
<td>LCD Screen 24”</td>
<td>3</td>
<td>3 x 25</td>
<td>0.65 C</td>
</tr>
<tr>
<td>Notebook + dock station</td>
<td>2</td>
<td>2 x 50</td>
<td>0.5 C</td>
</tr>
<tr>
<td>Stereo speakers</td>
<td>1</td>
<td>10</td>
<td>0.5 L</td>
</tr>
<tr>
<td>Colour Laser Printer</td>
<td>1</td>
<td>1050</td>
<td>0.99 L</td>
</tr>
<tr>
<td>Microwave oven</td>
<td>1</td>
<td>1160</td>
<td>0.93 L</td>
</tr>
<tr>
<td>Kettle</td>
<td>1</td>
<td>960</td>
<td>1.0 R</td>
</tr>
<tr>
<td>Refrigerator</td>
<td>1</td>
<td>150</td>
<td>0.52 L</td>
</tr>
<tr>
<td>LCD TV 32”</td>
<td>1</td>
<td>110</td>
<td>0.85 C</td>
</tr>
<tr>
<td>Solar collector accessories</td>
<td>1</td>
<td>80</td>
<td>0.9 L</td>
</tr>
<tr>
<td>Programmable load</td>
<td>1</td>
<td>0 - 4000</td>
<td>0.5L; 0.95L; 0.5C; 0.95C; 1R</td>
</tr>
<tr>
<td>AC/Heating</td>
<td>1</td>
<td>1400/2000</td>
<td>0.9 L</td>
</tr>
<tr>
<td>Hot water heating</td>
<td>1</td>
<td>550</td>
<td>1R</td>
</tr>
</tbody>
</table>

The simulation tool, called Programmable load, has been developed to simulate various power scenarios for different energy units. The programmable load is composed of RLC elements at a level of 230 V AC / 50 Hz. The load is adjustable at 100 W AC steps up to 4 kW AC with a power factor of 0.5, 0.95 and 0.99 for both the inductive and capacitive type of load and 1.0 for the pure resistance load. This tool can simulate a common home appliance – e.g. a washing machine, a hoover, an oven etc. or the entire daily load curve of a selected energy unit.

2.5. Monitoring system

In 2012 was developed comprehensive monitoring and remote control system, which is able to define the energy flows inside the system [P10], [P23], [P25]. This software was created in LabVIEW™ (Laboratory Virtual Instrument Engineering Workbench), sometimes known as G-language (Graphic language) that uses icons instead of lines of text to create an application. This virtual instrumentation tool is suitable for programming measuring and analysing signals as well as for management and visualization of technological process of complicated system.

The monitoring system can be divided into three basic parts – electric energy parts, solar energy parts and weather stations. Voltage and current converters are used to measure voltage, current and subsequently the powers parameters in electric energy part. In solar energy part is used
RS232 communication interface to obtain the basic parameters of solar collector from solar collector control unit. Other part of monitoring system is the weather station which allows evaluating of meteorological conditions in order to compare the overall system efficiency for variety climatic conditions. All results are saved into a database for subsequent post-processing.

As has been mentioned above, for electric parts of this system are used voltage and current converters. Voltage converters are two ranges voltage to voltage converters with $\pm 10$ V output, wide-frequency range $0 – 100$ kHz, galvanic isolation of input, output and power supply and low temperature fluctuation. It allows to measure voltage up to 600 V AC/DC. Another advantage of this converter is voltage withstanding up to 1000 V at $t < 1$ s.

Current measuring is also represented by two ranges current to voltage converters with the same positive qualities. Current converters dispose of minimal resistance in the primary circuit, what allows to measure the current up to 25 A AC/DC and the current withstanding is up to 36 A at $t < 1$ s.

For measuring the electrical values of batteries are used another type of converters, because of their properties. Nickel - Cadmium batteries are operated at 24 V level and the maximum possible charging current can be up to 140 A. In order to measure this current there is used a clamp ammeter converter. In this hardware parts have been used 28 converters and 2 DAQ multifunction cards. Measuring chain is built modular, which means effortless extension of this system in the future. This measuring chain uncovered the possibility of increasing the efficiency and effectiveness of energy management.

Fig. 10 Block scheme of data acquisition
The main application is created by tabbed system and its on-line visualization can be found in Fig. 11 and [37]. The cornerstone of the application is data acquisition (DAQ Assistant). “Select signal” VI’s have been used to categorized individual signals for consequent operation. “Express filters” VIs have to be used, because of high interference, because in different places and in the cabinets with measuring modules are crossing electrical and communication cables, e.g. photovoltaic part is DC type, wind generator has variable frequency 0 – 35 Hz, standard AC 50 Hz lines or Ethernet cables. To measure reliable signals have been a calibration of individual measuring module in measuring spectrum carried out.

Data storing is realized in several loops and measuring runs in one-second intervals. After 60 seconds (60 Values) are at those values applied “Mean” function to achieve one minute mean which has greater exploratory value, than average value. With all of these parameters is possible to carry out a post-processing, further determine the effectiveness of individual components. Into output file in the DD_MM_YYYY.txt format is saved 92 values, from voltages and currents, through meteorological values up to shaft’s torque of wind turbine.
The developed monitoring system allowed achieving partial results in the form of measurement database. By using these values it is possible to achieve a better idea of the individual components of the system, such as power curves, utilization ratio, etc.

Necessary data from monitoring system are converted and send to [37] in XML format and serves as input information of ADSM control Algorithm, for detail see Code example 1.

Code example 1 XML dataset from monitoring system

```xml
<TestData>
  <Date>28.8.2014 14:24:58</Date>
  <P_GEN>0.075768</P_GEN>
  <P_WB>1.294960</P_WB>
  <P_FVE2>-574.415102</P_FVE2>
  <P_FVE1>-890.822256</P_FVE1>
  <P_SB>-1353.696823</P_SB>
  <P_SI_adjust>-390.680554</P_SI_adjust>
  <f_SI>49.996102</f_SI>
  <P_BAT>415.121193</P_BAT>
  <U_BAT>26.482010</U_BAT>
  <P_Generator>0.017976</P_Generator>
  <Global_Irradiation>353.799238</Global_Irradiation>
  <WS_Meteo>2.700000</WS_Meteo>
  <Air_Temperature>23.100000</Air_Temperature>
  <Humidity>46.100000</Humidity>
  <ATM_Pressure>985.200000</ATM_Pressure>
  <Wind_Direction>163.000000</Wind_Direction>
  <freq_GEN>0.000000</freq_GEN>
</TestData>
```

2.6. Control system

Control system of AEU has been developed and based on hardware’s requirements and system modularity, which is able to be effortless extended. There are used action switching member to control the appliance input powered from the Off-Grid system. See Fig. 12 for wiring diagram of control system. The basic requirements of system installation in energy units include the lighting and socket control, heating control, cooling and ventilation, control of sunblind’s and curtains or other objects. Next, optimization of power consumption and cooperation with an electronic security system and fire alarm system. All of these requirements need to be visualized for consumer’s overview.
The system installations can be realized e.g. by using the "intelligent" electrical installations [38] or a product based on the industrial PC [39]. These installations allow the simplicity and high comfort of the controlling. By using these systems, there can be set the options for lighting scenes, motion sensors, heating settings, depending on the individual needs of the consumer/user.

Fig. 12 Control system wiring diagram
The "intelligent" installations, using actors to achieve the desired task/status, based on the orders of the management unit and the information obtained from the various sensors, such as temperature sensors, smoke detectors, weather station data and others. However, it is assumed, that these systems are connected into regular distribution system, and therefore is not envisaged the possibility of the lack of electric energy. In this case, must be taken into account different character and energy performance rating of individual appliances or groups of appliances. To control the individual appliance in the case of lack of the energy will deal with the proposed algorithm of ADSM.

The selected action switching members (actors) are able to open or close selected contact based on ADSM instructions, where is connected given appliance or group of appliances with the same priority.
3. CORRELATION ANALYSIS BETWEEN VARIABLES

This chapter describes the correlation analysis between variables in accordance with the accepted thesis of the state doctoral examination. Correlation analysis is extremely important to understand the relations and dependencies between electric power parameters, meteorological parameters and power quality parameters in Off-Grid system.

The development of autonomous energy systems is accompanied by a number of challenges related to the specific characteristics of these systems, which need to be successfully solved to become a real and viable system. The Off-Grid systems are very specific in many ways and aspects. As has been mentioned above, in most cases are generally discussing the benefits and proactive development directions of these concepts only, but as usually with every product, there is no longer mentions the issues of the operations in long time term and disadvantages of operation in some cases.

Table 8 List of variables used in the correlations analysis

<table>
<thead>
<tr>
<th>Input Parameters</th>
<th>Type of Variable</th>
<th>Description</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>WD</td>
<td>Input</td>
<td>Wind Direction</td>
<td>°C</td>
</tr>
<tr>
<td>WS</td>
<td>Input</td>
<td>Wind Speed</td>
<td>m·s⁻¹</td>
</tr>
<tr>
<td>GSR</td>
<td>Input</td>
<td>Global Solar Radiation</td>
<td>W·m⁻²</td>
</tr>
<tr>
<td>Temp</td>
<td>Input</td>
<td>Air Temperature</td>
<td>°C</td>
</tr>
<tr>
<td>Hum</td>
<td>Input</td>
<td>Relative Humidity</td>
<td>%</td>
</tr>
<tr>
<td>AtmP</td>
<td>Input</td>
<td>Atmospheric Pressure</td>
<td>hPa</td>
</tr>
<tr>
<td>P_Consump</td>
<td>Input / Output</td>
<td>Power Consumption</td>
<td>W</td>
</tr>
<tr>
<td>P_PV</td>
<td>Output</td>
<td>PV Output Power</td>
<td>W</td>
</tr>
<tr>
<td>P_WPP</td>
<td>Output</td>
<td>WPP Output Power</td>
<td>W</td>
</tr>
<tr>
<td>Pₕ₁</td>
<td>Output</td>
<td>Long Term Flicker Severity</td>
<td>-</td>
</tr>
<tr>
<td>THD_U</td>
<td>Output</td>
<td>Total Harmonic Voltage Distortion</td>
<td>%</td>
</tr>
<tr>
<td>THDₖ</td>
<td>Output</td>
<td>Total Harmonic Current Distortion</td>
<td>%</td>
</tr>
<tr>
<td>Freq</td>
<td>Output</td>
<td>Power Frequency</td>
<td>Hz</td>
</tr>
</tbody>
</table>

The basic technical problems of mentioned Off-Grid and Smart-Grid systems are the issues of power flow control inside the energy units, development of new protection systems, power quality
and last but not least the ADSM. As it was mentioned in previous chapter, there has been developed comprehensive monitoring system, and data from this system such as weather conditions like humidity, temperature, global solar radiation, user’s consumption, power production etc., are used to find the relations between variables (summarized in Table 8).

For better understanding of the operation problematic it can be helpful to use the statistical correlations to evaluate the strength of the relations between variables in the Off-Grid system. This analysis deals with the relation strength between variable, such as weather conditions and power production and consumption as well as for power quality variables [16], [17]. Following equation (2) has been used to obtain the correlation coefficient:

\[
\text{Correl}(X,Y) = \frac{\sum (x - \bar{x})(y - \bar{y})}{\sqrt{\sum (x - \bar{x})^2 \sum (y - \bar{y})}}
\]

where \(\bar{x}\) and \(\bar{y}\) are the sample means of average data array 1 and of data array 2.

\[\text{Correl}(X,Y) = \frac{\sum (x - \bar{x})(y - \bar{y})}{\sqrt{\sum (x - \bar{x})^2 \sum (y - \bar{y})}}, \quad (2)\]

Fig. 13 Graphical correlation analysis between weather and power input/output variables

Fig. 13 depicts relations between weather and power variables, while higher point in the picture means deeper relations between selected variable, e.g. GSR and \(P_{PV}\) are close related, because when is the sunny day, the GSR value is high what causes the high PV output production. Same situation occurs in the case of WPP, when the wind speed is high the WPP power output increase
Correlation analysis between variables

as well. The correlations with value lower than zero does not stands for strictly uncorrelated progress, only sais that move of one variable could leads to move of other variable but in opposite direction.

These exogenous variables were obtained with hypothesis, that using variables that describe the conditions will be leading forecasting as a result [P3], [P14], [P22]. This approach comes to first task – to filter the variables with zero-impact to the predicted variables. To compute the relations between these time series, there was used simple correlation computation as well as in previous Weather-Power analysis and results was arranged into matrix where each row represents the amounts of correlations to one predicted time set, see results in Fig. 14. As it can be seen, the highest correlation level was found between global solar radiation level and the frequency.

![Graphical correlation analysis between weather and power quality variables](image)

**Fig. 14 Graphical correlation analysis between weather and power quality variables**

The correlation values close to zero means that combination of that particular time set is not correlated at all and their progress does not depend on each other.
4. DESCRIPTION OF THE ACTIVE DEMAND SIDE MANAGEMENT

In this chapter will be described the control algorithm and the methods, which enable the intelligent rescheduling of the appliances during time periods. This chapter presents the unique approach for developed Active Demand Side Management solution for energy units and is the most important part of this doctoral thesis.

There is a story in Greek mythology about a tyrannical king named Minos. In short, Minos demanded a tribute in the form of young men and women to sacrifice them to the Minotaur – a fearsome beast with the head of a bull and the body of a man. The young sacrifice would be led to the labyrinth, where they would be eaten by the Minotaur before they could find their way out. This tragedy continued until young Theseus of Athens volunteered to be one of the sacrifices. Following the advice of Minos’s daughter Ariadne, Theseus entered the labyrinth with a sword and a ball of string. After slaying the monster, Theseus was able to find his way back to the exit by unwinding the string as he went along. Based on this story can be explained the solution strategy of Backtracking Algorithms. [40]

Backtracking can be useful for many real-world problems. The solution process consists of working your way through a sequence of decision points in which each choice leads you further along some path. If you make the correct set of choices, you end up at the solution. On the other hand, if you reach a dead end or otherwise discover that you have made an incorrect choice somewhere along the way, you have to backtrack to a previous decision point and try a different path. Algorithms that use this approach are called backtracking algorithms.

The basic strategy is to write programs that can backtrack to previous decision points if those choices lead to dead ends or to wrong decision. By exploiting the power of recursion, however, you can avoid coding the details of the backtracking process explicitly and develop general solution strategies that apply to a wide variety of problem domains.

Backtracking as solution tool/method can be used to solve maze or 2 player game, such as tic-tac-toe or chess. On following Fig. 15 is presented “minmax” strategy and the heart of this strategy is the function “FindBestMove”. The role of the functions to return the optimal move in that position.
The current state is represented by a dot at the top of the game tree. If there are, for example, three possible moves from this position, there will be three lines emanating down from the current state to three new states that represent the results of these moves. For each of these new positions the opponent will also have, let’s say three options. In order to achieve a sense of how you should proceed, it helps to add some quantitative data to the analysis. Determine whether a particular move is better than some alternative is much easier if it is possible to assign a numeric score to each possible move. The higher the numeric score, the better the move. This Algorithm consists of two mutually recursive functions, one that finds the best move and another than evaluates the quality of a position. To make it as general as possible it has to be used the following extension: [40]

- It must be possible to limit the depth of the recursive search
- It must be possible to assign ratings to moves and positions.

Backtracking Algorithms are implemented into the ADSM to be attended about the energy planning requirements as well as for predicted energy. In the case when is enough energy to perform all appliances in all priorities, the ADSM is planning the consumption scenario with no changes. However, in the case of lack of energy is the ADSM looking for the best way how to
spread out the energy in selected time period, what means in fact, move forward or backward in time of some appliances in the selected priority.

The ADSM consists of 2 basic parts, which are essential for its proper functioning. The 1st part of ADSM consists of weather forecast, energy forecast and consumption forecast and in the near future will be the ADSM extended of Power Quality predictor and new protection concept. The 2nd part of ADSM is control module and used Algorithm.

In short, the ADSM needs to know the amount of energy for the appliances for current day or time period together with predictions of available energy from weather forecasts and the available amount of energy in batteries. These factors help to plan and spread out the energy to appliances according to their priorities and in the case of surplus of energy to store the energy efficiently in the battery bank for later use.

The ADSM can be characterized as a software part of the Active Energy unit and following sub-chapters will describe the inputs of this comprehensive system.

4.1. Weather and Energy Forecast

Weather forecast is very complicated and complex discipline and it is not easy to implement. At present time the system uses data from the national information systems that provide a localized prediction according to the position of the system. The weather forecast is particularly important for the prediction of solar radiation and the amount of clouds due to use of solar panels and the wind speed prediction for wind power plants. The weather forecasting module is connected to the national/regional weather forecasting agency and periodically downloads the data for the weather forecast at the specified locations.

In previous cooperation of research the team has been developed the energy forecast tool for PV and WPP power output using artificial intelligence methods. As a member of research team I have dealt with energy forecast supporting information such as creating databases, data sorting and verifying the results. Based on supporting information and created databases have been developed, verified and put into operation energy forecast tools called “Energy Predictors”, while evaluation and initial applications of methods able to predict the stochastic production may be found in [41]. Artificial neural networks were used for short-term and mid-term solar power forecast in [42] and [43]. Gaussian equations were tested and applied in [44] to estimate the solar power output.
Statistical short-term forecasting system for grid-connected photovoltaic plant was presented in [45]. Application of hybrid multilayer feed forward neural network technique for photovoltaic power plant output estimation was presented in [46]. A practical method for solar irradiance forecast was shown in [47]. The method used in this system is based on the neural networks and the Fuzzy prediction. The algorithm was presented in the [48].

![Comparison between predicted and measured values of PV power output and GSR](image.png)

*Fig. 16 Comparison between predicted and measured values of PV power output and GSR*

Such as example of Energy forecast tool see Fig. 16, where are compared real measured and predicted values of GSR and PV power output. The differences, summarized in Table 9, are caused by PV forecast model, because the developed forecast tool is based on the grid-connected PV database and PV power output in the Off-Grid system is influenced by actual Battery SoC, current user consumption, power frequency, etc. The important task in the near future will be the optimization of PV power output prediction, especially for the Off-Grid system, which is more complicated than for grid-connected PV.
Table 9 Forecasted and measured PV energy output

<table>
<thead>
<tr>
<th>Day</th>
<th>Forecasted Energy (kW·h)</th>
<th>Measured Energy (kW·h)</th>
<th>Differences (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2014/07/24</td>
<td>6.65</td>
<td>7.36</td>
<td>-9.80</td>
</tr>
<tr>
<td>2014/07/25</td>
<td>12.41</td>
<td>15.38</td>
<td>-19.35</td>
</tr>
<tr>
<td>2014/07/27</td>
<td>23.89</td>
<td>20.86</td>
<td>+14.56</td>
</tr>
<tr>
<td>Total</td>
<td>62.72</td>
<td>64.67</td>
<td>-3.02</td>
</tr>
</tbody>
</table>

4.2. Consumption plan – forecast

Consumption plan is another very important input, which is essential for proper functioning of ADSM. The consumption plan is expressed with sum of power inputs of individual appliances during the time. This sum of power inputs during the day creates the Daily Load Curve (DLC).

Fig. 17 shows the real-measured waveforms of appliances power inputs (Refrigerator and Washing machine) and their conversion into a simplified power blocks, when the integration of the areas under the curve are equal in both cases, i.e. it is the substitution of actual power input curve to the power blocks. The block substitution was used to simplify the energy calculation in the computing hardware as well as to set the same time stamp in the ADSM, because a 5min interval is suitable throughout the data, which is used in, e.g. the appliance cycle, data measuring, time needed to recalculate if certain changes in the consumption plan occur, etc.
This substitution is now carried out in the five minute intervals, while next step is increasing the accuracy and decreasing the time stamp up to one minute interval. Currently, is one minute time stamp maximal resolution with regards to the computing hardware, where ADSM is running in.

The ADSM uses specific rule to break up the appliance cycle, because some blocks of the appliance can be divided during the time. In the first case, when is the divisibility allowed, e.g. in heating, when the result of discontinuities in time blocks is the reduction of the temperature in the room (or water) and lifespan of heating element is not decreasing. In the second case, when is the divisibility not allowed, because the process/cycle does not allow it, this discontinuities can have a major effect on the service life of the appliance, e.g. for the washing machine when is the power input disconnected during the washing cycle and then reconnected, the washing cycle begins again from start, depending on the specific type of washing machine.

Table 10 defines the power blocks of used appliances in the Off-Grid System. Their real waveforms are converted to standardized power blocks using substitution mentioned above.
### Table 10 Overview of Appliances parameters

<table>
<thead>
<tr>
<th>Appliance Name</th>
<th>5min blocks interval in 1 hour / cycle interval (W)</th>
<th>Block Frequency per day</th>
<th>Priority</th>
</tr>
</thead>
<tbody>
<tr>
<td>Refrigerator</td>
<td>0 0 0 150 150 150 0 0 0 150 150 150</td>
<td>72</td>
<td>0</td>
</tr>
<tr>
<td>Hot water</td>
<td>550 550 550 550 550 550 550 550 550 550 550</td>
<td>12</td>
<td>0</td>
</tr>
<tr>
<td>Power Circuit 1</td>
<td>70 70 70 70 70 70 70 70 70 70 70</td>
<td>84</td>
<td>0</td>
</tr>
<tr>
<td>Power Circuit 2</td>
<td>110 110 110 110 110 110 110 110 110 110 110</td>
<td>96</td>
<td>0</td>
</tr>
<tr>
<td>Heating accessories</td>
<td>10 10 10 10 10 10 80 80 80 80 80</td>
<td>144</td>
<td>1</td>
</tr>
<tr>
<td>Electric Kettle</td>
<td>960 0 0 0 0 0 0 0 0 0 0 0</td>
<td>4</td>
<td>1</td>
</tr>
<tr>
<td>Microwave oven</td>
<td>1160 0 0 0 0 0 0 0 0 0 0 0</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Air Condition</td>
<td>1400 1400 1400 1400 1400 1400 1400 1400 1400 1400 1400</td>
<td>126</td>
<td>1</td>
</tr>
<tr>
<td>Heating (AC)</td>
<td>1500 1500 1500 1500 1500 1500 1500 1500 1500 1500 1500</td>
<td>71</td>
<td>1</td>
</tr>
<tr>
<td>Simulated Stovetop</td>
<td>1500 1500 1500 1500 1500 1500 1500 1500 1500 1500 1500</td>
<td>12</td>
<td>2</td>
</tr>
<tr>
<td>Laser Printer</td>
<td>1100 0 0 0 0 0 0 0 0 0 0 0</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>LCD TV</td>
<td>110 110 110 110 110 110 110 110 110 110 110 110 110 110 110 110 110 110 110 110 110 110</td>
<td>96</td>
<td>2</td>
</tr>
</tbody>
</table>

The DLC is next fundamental parameters for the correct function of the ADSM and is implemented in computational core of the ADSM. For annual operation can be defined DLC for each annual period. DLC is defined in each annual period for the weekday and for the weekend, when consumers’ habits are slightly different. DLC is currently divided into four seasons - winter, spring, summer and autumn and each period on the workdays and the weekends.

Table 11 provides an overview of the energy requirements for the standard day/week for each period (5 working days and 2 weekend days) of used appliances summarized in Table 10 and their energy requirements.
Table 11 Energy requirements during the year

<table>
<thead>
<tr>
<th>Season</th>
<th>Energy requirement per working day (kW·h)</th>
<th>Energy requirement per weekend day (kW·h)</th>
<th>Energy requirement per week (kW·h)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spring</td>
<td>16.07</td>
<td>17.66</td>
<td>115.67</td>
</tr>
<tr>
<td>Summer</td>
<td>22.72</td>
<td>22.39</td>
<td>158.37</td>
</tr>
<tr>
<td>Autumn</td>
<td>18.67</td>
<td>20.26</td>
<td>133.87</td>
</tr>
<tr>
<td>Winter</td>
<td>19.89</td>
<td>20.30</td>
<td>140.05</td>
</tr>
</tbody>
</table>

Code example 2 defines the appliance setting and definition below. Each appliance has several classifiers, such as ID, name, priority etc., using this classifiers is the appliance defined in internal structure of ADSM. E.g. Divisibility is characteristic classifier to break up rule mentioned above and if there is “0” parameter the appliance cycle cannot to be break up.

**Code example 2 Appliance definition format in ADSM**

```plaintext
appliance
  id = 53
  name = Air Condition
  priority = 1
  divisibility = 0
  movable = 1
  canmoveback = 1
  maxMove = 24
  stoppable = 1
  blocks
    1400
    1400
    1400
    1400
    1400
    1400
    1400
    1400
    1400
  end
end
```
The 1st column in the Code example 3 above means the time axis, when the numbers represent time period in 5min interval. The other numbers in the row represent selected appliance in ID format (e.g. 53 is AC unit) with pre-set time length of working cycle. The forecast of consumption is carried out based on a consumption plan.

Code example 4 shows how is defined the used generators in the ADSM. Their time plan has similar structure as in Code Example 3.
The results of the power consumption and power output forecast, as well as a timetable for turning on of appliances are the entry for the control module.

Next very important rule is implemented in the ADSM – Manual Appliance Start. There can occurs the situation, when the user would like to e.g. do a coffee quite earlier or later, or came later from the work and just want to reheat some food in the microwave, etc. Web pages of appliance control system has been developed for this reason (in version 1.0), to see which appliance is running and with possibilities to change outputs to “DIS” (disable), “OFF” and “ON” status. Based on the output status is send information to the ADSM in Appliance. The plan and the control algorithm have to recalculate the available energy and in following time period switch on the output. Next version of the Manual appliance web pages will be more user-friendly and then can be converted to current smart phones operating systems such as Android, IOS or Windows Phone as an application.

![Web pages of manual appliance start](image)

Fig. 18 Web pages of manual appliance start

Fig. 19 shows the DLC for selected time period in the year – summer working day. This figure depicts color-coded priorities of individual appliance groups and their sums of power inputs in each
priority and then the sum of required energy in the whole Off-Grid system. The power input is related to the nominal power of the Central inverter (see Table 4). Central inverter efficiency is related to the Central inverter loading, when 100% load is achieved, according to the manufacturer’s claim, efficiency should be up to 94.5%. Each DLC respects the consumer habits as well as the highest comfort setting. This comfort level changes depending on the available energy from the Source part, Battery bank SoC and Weather forecasts.

![Example of Daily Load Curve in summer – working day](image)

*Fig. 19 Example of Daily Load Curve in summer – working day*
In parallel with the development of the ADSM was running long-time experimental measurement on various types of objects, e.g. family houses, flats, administrative buildings or commercial/industrial buildings. The results of this measurement will be evaluated and implemented using programmable load and will be able to simulate the different energy requirements on different objects under various conditions, thereby the possibility the ADSM of application will be increased.

4.3. Control module and Algorithm

The Control module uses a deterministic algorithm and backtracking. This algorithm is designed as a universal scheduling algorithm which plans the appliances at the time when the production of the power sources is sufficient. First, the input data will be described and then the scheduling algorithm itself. Each power source is described by name along with the history of the power production. This information is used for power output prediction. The output prediction is used as a good approximation of the actual power output based on the actual weather forecast.

Each appliance has a name, priority, flags and a definition of a typical run of a one cycle of the appliance. The typical run is divided into blocks. The length of the blocks is fixed and it is a constant among the entire module and scheduling process. With the decreasing length of the block, the precision of the scheduling process increases, but also increases the requirements on the precision of the power output forecast and also the time of the scheduling slightly increases.

Several types of the appliances exist in a system. The first type is a regular one. These appliances are scheduled regularly in a day such as heating, refrigerator, air condition etc. The second type is random type such as lights, which cannot be scheduled at all but has a different probability in each day of week (e.g. cleaner) or a day time (e.g. night). The last type is occasional appliances which may be moved among a day such as washing machine or dish washer. The regular appliances are planned as they require but they may be moved in a small interval around the planned time. The random appliances cannot be moved, but fortunately, such appliances have usually small consumptions and/or short running time. The occasional appliances may be moved in large interval around the planned time and even between days.

Each occurrence of appliances is called appliance cycle. The cycles are scheduled in a plan.
The 1st step of the algorithm is the sorting of the appliance plan according to the appliance’s priorities. I distinguish between three levels of priority 0, 1, 2. Priority “0” is the most important and appliances in this priority are necessary for human life, e.g. heating for thermal comfort, a refrigerator to keep the foods fresh, etc. Priority “2” is the lowest and the appliances in this priority are mostly for comfort such as a TV. The appliance cycles are sorted according to the priority from the highest to lowest in importance. The presented ADSM concept is actually used in a pilot testing laboratory, where the priorities are somewhat different than in regular households – e.g. TV is on priority level “2”, because is it a displaying tool for a security system and is not used for regular TV watching. It should also be noted, that the priority of the individual appliances are selected based on user requirements and can be dynamically changed. In order to increase the user comfort level as much as possible, there is a possibility to switch on an individual appliance through a web interface for a selected time period and control the current appliances status. In this case, this information is dynamically imported to the ADSM computing core and the selected appliance is temporarily assigned priority level “0”. However, this can cause a lack of energy to the power supplying of e.g. a refrigerator, a microwave, etc. in the worst case scenario.

The 2nd step is iteration through the periods and in each period sums the total energy required by the appliances, the total energy produced by the power sources and the available energy in the battery bank. When the amount of required energy is lower than the total amount of available energy from the power source and battery bank, then no operation occurs and the algorithm moves to the next interval. When the required energy is even lower than the energy produced by the power sources, the remaining energy is used for charging of the battery bank. When the required energy is higher than the amount of energy produced by the power sources and lower than the total available energy, than the battery bank is used as an additional power source and its energy level is decreased.

When the energy required by the appliances is even higher than the total available energy then a rescheduling of the appliance cycles is performed, see the decision block in Fig. 21. Those appliances which cannot be moved are left as they are, but the appliances which may be moved are moved to previous or next period. A problem occurs when the moved cycle should be moved in the middle of its run, e.g. from its 3rd block. Two possible options exist. The 1st option is that the cycle may be broken up, and then only the rest of the appliance cycle is moved to the following
period. When it cannot be broken up, the cycle is moved anyway but the scheduling algorithm moves back to the period in which the moved cycle began originally.

In the 2nd option the algorithm must solve the problem when the moved cycle of an appliance collides with another cycle of the same appliance. In this case the latter cycles are postponed as well, etc. When the cycle is postponed and moves out from the scheduled window, it is removed from the system and is disabled. The algorithm moves forward and backward until the appliance cycle energy request in all the periods are satisfied or disabled.

The ADSM function can be described in a model situation, where the system will control the power flows in the energy unit with expected changeable weather. Block scheme of AEU is shown in Fig. 20. Individual sequences of control system can be defined as:

1. The weather forecasting tool determines the 2-days weather forecast and the expected scenario of electricity consumption with different appliances throughout the day.
2. The energy forecasting tool determines the value of available energy from PV, WPP and determines, if this amount of energy is enough to cover the expected power consumption scenarios.
3. ADSM accepts all three information inputs (weather forecast, consumption forecast, energy forecast) and spreads out the energy over this period using the energy storage device. The surplus of energy will be stored and the energy deficit will be covered from the energy storage device.
4. The priority of individual home appliances is respected in the switching process based on the supervision and their nature.
5. In the event of a lack of energy in the system in the selected consumption scenarios, the Active demand side management system has to suggest different consumption respecting the load priorities – e.g. a delayed start to the selected appliances – kettle, washing machine, dishwasher, TV, etc.)
Fig. 20 Block scheme of the active energy unit
Fig. 21 ADSM Main Algorithm Flowchart

Fig. 21 depicts the basic flowchart of used algorithm in the ADSM. This algorithm is designed as a universal algorithm and can be implemented to any energy self-sufficient objects using input/output modification. The inputs and initial operations are included in “Initialization Sub-Algorithm” below. If the initialization operation was successful the main algorithm can continue in the calculating the power requirements such as total energy generation represented by $E_{GEN}$ variable, total energy consumption represented by $E_{LOAD}$ variable and available energy in battery bank summarized in $E_{BAT}$. In the case when (3),
and all blocks are covered, ADSM store the energy surplus into battery bank. In the case when the requested energy is lower than available, the ADSM must choose different energy strategy (scenario) described in Fig. 23 and Fig. 24. Finally if all blocks is covered or moved out of the monitored n-days plan the algorithm is finished for current time plan.
“Appliance.plan”, see Code example 3. After loading these files can system create block consumption plan and sort the appliances by their priority.

![Flowchart Sub-Algorithm](image)

*Fig. 23 “Uncovered block selection” Flowchart Sub-Algorithm*

Fig. 23 depicts the selection of uncovered blocks for subsequent post-processing. First, ADSM sorts out the appliances blocks in ascending order according to appliance priority than ADSM chooses the uncovered blocks, in highest priority, and sums up the total consumption. In the case when the consumption is less or equal than available energy, ADSM marks selected blocks as covered, if the total consumption of selected blocks is higher than available energy, ADSM marks these blocks as uncovered and return all of them to following step in “Main Algorithm – identify
each uncovered block in selected appliance plan”. The task of this sub-algorithm is to determine the uncovered blocks and select the appliance cycle which cannot to be energy covered.

![Flowchart Sub-Algorithm](image)

**Fig. 24 “Determine the new plan start for uncovered appliance” Flowchart Sub-Algorithm**
Fig. 24 shows the decision process of determining the new starting plan for uncovered appliance. If we take into account the previous decision in this step – we operate just with the uncovered blocks (cycles) only, we do following steps to cover or discard the appliance cycles. From inputs are selected appliance characteristics and the ADSM is trying to search suitable time sequence where the system can be moved (rescheduled), in fact, the ADSM tries to search time sequence, where is enough available energy to cover the appliance consumption. If the ADSM did not find suitable time period in past it will try it in the future time periods. The ADSM is searching suitable time sequences until it is possible due to maximal time plan. The maximal time plan limit is actually set to two days in accordance to weather and consequently energy forecast accuracy. If the ADSM is unsuccessful to find suitable time sequence in the future, than it discards the entire appliance cycle from the plan.
5. TECHNO-ECONOMIC ANALYSIS

The techno-economic analysis of the Off-Grid system is carried out in this chapter. The developed system at the university campus is primarily intended for experimental measurement and testing of various faults and abnormal conditions, therefore occasional downtimes in the system are present. This is the reason, why the analysis is based on a model example. Although the current findings are included, all the necessary components are added and the weather conditions are based on actual measurements [P15]. Based on the analysis, there is a possibility to build up and operate the entire system under the ADSM.

The following Table 12 is a list of items that are necessary for the proper function of the entire system. A techno-economic analysis is carried out for the 2 variants of the operation. In the 1st variant (VAR1), there is a parallel cooperation of WPP, PV, Battery bank and LPG Generator. The 2nd variant (VAR2) of operation is with the same items, apart from WPP. The total price at the time of the writing of this doctoral thesis was for VAR1 $45,676 and for VAR2 $32,435 with currency conversion (1 USD = 25.73 CZK).

Table 12 Components used in Active Energy Unit

<table>
<thead>
<tr>
<th>Items</th>
<th>Sub-Items</th>
<th>VAR1 (%)</th>
<th>VAR2 (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Axial WPP 5 kW</td>
<td>Generator, Controller, 5m Roof top Tower</td>
<td>27.44</td>
<td>0.00</td>
</tr>
<tr>
<td>PV 5 kWp</td>
<td>20 pcs. of Poly. panels, MPPT Regulator</td>
<td>12.27</td>
<td>16.90</td>
</tr>
<tr>
<td>4.4 kW LPG Generator</td>
<td>-</td>
<td>2.31</td>
<td>3.18</td>
</tr>
<tr>
<td>Battery bank 760 A·h</td>
<td>Cases, Conductors, DC protection, etc.</td>
<td>43.64</td>
<td>60.14</td>
</tr>
<tr>
<td>Weather Station</td>
<td>-</td>
<td>0.72</td>
<td>1.00</td>
</tr>
<tr>
<td>Monitoring Part</td>
<td>4Q electrometer</td>
<td>0.38</td>
<td>0.53</td>
</tr>
<tr>
<td>Controlling Part</td>
<td>PC, I/O Module, Relays, Contactors</td>
<td>1.02</td>
<td>1.40</td>
</tr>
<tr>
<td>6 kW Hybrid Inverter</td>
<td>-</td>
<td>9.96</td>
<td>13.72</td>
</tr>
<tr>
<td>Additional materials</td>
<td>Cables, Protection system, Cabinets, etc.</td>
<td>2.26</td>
<td>3.12</td>
</tr>
<tr>
<td>Total</td>
<td>-</td>
<td>100.00</td>
<td>100.00</td>
</tr>
</tbody>
</table>
All of the used components are selected based on the relevance to the residential home power level situated in the Central Europe. In the Table 12 are used relative prices to the amounts indicated above for better clarity how financially demanding are the component in comparing to each other.

It should be noted that the prices for each item are based on the currently available prices of the e-shops. These prices, however, cannot be understood as a final, because if the idea of commercially available product, which will be competitive and profitable, will come true, then it can be assumed that prices will be reduced more than 30% of the current value.

As WPP has been selected as the wind power plant with a vertical axis of rotation with synchronous generator with permanent magnets (PMSG). These generators are characterized by high reliability and types with vertical axis of rotation do not need to be equipped with the controlling system to deviates the nacelle from wind direction in case of unfavourable weather conditions. Another advantage of PMSG is not the need for reactive energy resources as in the case of asynchronous generators, or excitation windings units as in the case with external excitation of synchronous generators.

PV is in this case consists of 20 pieces of polycrystalline panels that make up the installed power of 5 kWp. Selection of PV panel technology is closely related to the place of installation of the system, because in different places is suitable to install polycrystalline instead of monocrytalline PV cell technology depending on the geographical and geomorphological conditions.

The LPG Generator is used as an additional source of electric energy, for the cases of lack of energy, during energy peaks or for keeping the battery bank lifespan. This additional power source is considered as environment-friendly. The classic distribution network in this case is not mentioned, because pure Off-Grid mode is expected. However, in the case of the comprehensive Smart-Grid system, with expansion of e-cars, the option with a possible appears this option very useful. The biggest financial expense represents a battery bank. Actually are lithium based batteries considered for one of the best solution for Off-Grid application, due to their properties in the form of a DoD up to 90%, a large current load capacities and stable number of discharge cycles regardless of the charging status.
Another very important part of the system is a hybrid inverter, because it takes care about creating a standard AC distribution network. Other items such as the weather station, protection system, controlling and monitoring part etc. are only about 6% of the total cost. These costs are essentially fixed for almost any modern wiring system.

**Techno-Economic Analysis using HOMER model**

The HOMER is a computer model that simplifies the task of designing hybrid renewable Micro-grids, whether remote or attached to a larger grid. The HOMER’s optimization and sensitivity analysis algorithms are allowing to evaluate the economic and technical feasibility of a large number of technology options and to account for variations in technology costs and energy resource availability. Originally designed at the National Renewable Energy Laboratory for the village power program, the HOMER is now licensed to HOMER Energy [49].

The HOMER software tools provide a lot of settings options to make the Off-Grid/Micro-grid solution as similar as possible to the real conditions. In this analysis the inputs consist of individual Off-Grid components, DC coupling topology, annual consumption plan, weather conditions, etc. All of these inputs are based on the real components and measurements and the university campus has been used as a place of this simulation as well as for verification of this model. The basic simulation conditions can be found in Table 11 (Energy requirements) and Table 12 (Used components in AEU).

Techno-Economic analysis has been carried out for better imagination about the initial cost, cash flows, electric energy production during the year, battery bank states, electrification cost and the emissions. The simulation time is set to 25 years.

Fig. 25 depicts the cash flow summary in the form of Net Present Cost (NPC) categorized by component and in relative prices. There can be seen, that the battery bank has the major price effect of Initial Capital and total Net Present Cost in both cases. It is caused by battery setting, while the parameters are set to the real parameters of LiFePO4 battery bank and the life time is set to 14 years, then replacement of new battery bank is needed.
The fuel for LPG is needed as well as operation and maintenance (O&M) cost, which are much higher than in the case of VAR1. For converter and LPG Generator lifetime is set for 13 years of operation, while the replacement after this time period is necessary. Following Table 13 summarizes the basic financial indicator.

Table 13 Basic financial indicator of selected Off-Grid system

<table>
<thead>
<tr>
<th>Parameter</th>
<th>VAR1</th>
<th>VAR2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Initial Capital ($)</td>
<td>55,884</td>
<td>39,684</td>
</tr>
<tr>
<td>Operating Cost ($·yr$^{-1}$)</td>
<td>1,121</td>
<td>3,226</td>
</tr>
<tr>
<td>Total NPC ($)</td>
<td>70,218</td>
<td>80,923</td>
</tr>
<tr>
<td>Levelized COE* ($·kW·h$^{-1}$)</td>
<td>0.761</td>
<td>0.889</td>
</tr>
</tbody>
</table>

*COE is Cost of Energy.
Another helpful tool for comparison of the Off-Grid system with a standard Distribution network can be the Break-even Grid extension distance. This is the distance from the grid which makes the net present the cost of extending the grid equal to the net present cost of the Off-Grid system. The farther away it is from the grid, the more optimal the stand-alone system is. The nearer it is to the grid, the more optimal the grid extension is. The results are following, for VAR1 is the Break-even grid extension distance 4.87 km and for VAR2 it is 5.94 km. The initial setting for this sub-analysis is 8,000 $\cdot$ km\(^{-1}\) of capital cost excluding O&M cost and grid power price was set at 0.23 $\cdot$ kW$^{-1}$·h$^{-1}$.

![Fig. 26 Breakeven grid extension distance - electrification cost](image)

**Fig. 26 Breakeven grid extension distance - electrification cost**

Fig. 27 explains percentage of average monthly energy production in individual month of VAR1. The results are as expected, WPP produces most energy during winter and PV during summer time. LGP Generator produce enough energy to meet the load, when the Renewable source are not able to meet the current load, even there has been used the cycle charging strategy.

The cycle charging strategy is a dispatch strategy whereby whenever a generator needs to operate to serve the primary load, it operates at full output power. Surplus electrical production
Techno-economic analysis

goes toward the lower-priority objectives such as, in order of decreasing priority: serving the
deferrable load, charging the battery bank, and serving the electrolyser, of course if the components
are presented in the system. HOMER dispatches the controllable power sources (generators, battery
bank, grid) each time step of the simulation in a two-step process, when using the cycle charging
strategy. First, HOMER selects the optimal combination of power sources to serve the primary and
thermal load according to the load-following strategy. Then HOMER ramps up the output of each
generator in that optimal combination to its rated capacity, or as close as possible without causing
excess electricity.

Fig. 27 Example of Monthly Average Electric Energy Production in VAR1

In VAR1 the LPG Generator ran for 51 hours during the year and consumed 73 l of LPG, in
the VAR 2 it was 720 hours and 1,045 l of fuel. Table 14 summarizes the energy sub-analysis and
compares the selected two variants of operation, such as Energy production, excess and unmet
energy, or capacity shortage.
### Table 14 Simulations results of Electric energy parameters

<table>
<thead>
<tr>
<th></th>
<th>VAR1</th>
<th></th>
<th>VAR2</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>kW·h·yr⁻¹</td>
<td>%</td>
<td>kW·h·yr⁻¹</td>
<td>%</td>
</tr>
<tr>
<td><strong>Production</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>PV Array</td>
<td>5,307</td>
<td>49</td>
<td>5,307</td>
<td>63</td>
</tr>
<tr>
<td>Wind Turbine</td>
<td>5,391</td>
<td>49</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>LPG Generator</td>
<td>218</td>
<td>2</td>
<td>3,168</td>
<td>37</td>
</tr>
<tr>
<td><strong>Consumption</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>7,219</td>
<td>100</td>
<td>7,120</td>
<td>100</td>
</tr>
<tr>
<td><strong>Excess Electric Energy</strong></td>
<td>2,656</td>
<td>24.3</td>
<td>137</td>
<td>1.61</td>
</tr>
<tr>
<td><strong>Unmet Electric Load</strong></td>
<td>8.59</td>
<td>0.1</td>
<td>107</td>
<td>1.48</td>
</tr>
<tr>
<td><strong>Capacity shortage</strong></td>
<td>14.1</td>
<td>0.2</td>
<td>137</td>
<td>1.89</td>
</tr>
</tbody>
</table>

**Fig. 28 Comparison of battery bank state of charge during one year of system operation**

Fig. 28 depicts the rainbow chart of battery bank in relative SoC during one year of operation. There is significant difference between VAR1 (on top) and VAR2 (on bottom) in the SoC. According to the SoC limit in VAR2 some of the electric load was unmet (1.48 %) to keep battery lifetime. In simulation, was the DoD set to 90 %, what means 90 % of stored energy can be used in the system with no effect in battery lifetime or capacity shortage.

In simulation, two independent factors may limit the lifetime of the battery bank: the lifetime throughput and the battery float life. In other words, batteries can die either from use or from old age. In simulation can be used a rule, that the battery lifetime is limited by time, throughput, or both. HOMER calculates the battery bank life using following equation (4):
\[ R_{\text{batt}} = \left\{ \begin{array}{c} \frac{N_{\text{batt}} \cdot Q_{\text{lifetime}}}{Q_{\text{thrpt}}} \\
\frac{Q_{\text{thrpt}}}{R_{\text{batt}} \cdot f} \\
\text{MIN}\left( \frac{N_{\text{batt}} \cdot Q_{\text{lifetime}}}{Q_{\text{thrpt}}} \cdot R_{\text{batt}, f} \right) \end{array} \right\} \quad (4) \]

where \( R_{\text{batt}} \) is battery bank life (yr), \( N_{\text{batt}} \) is the number of batteries in the battery bank, \( Q_{\text{lifetime}} \) is lifetime throughput of a single battery (kW·h), \( Q_{\text{thrpt}} \) is annual battery throughput (kW·h·yr\(^{-1}\)) and \( R_{\text{batt}, f} \) is the battery float life (yr).

**Table 15 Emissions produced by Off-Grid system**

<table>
<thead>
<tr>
<th>Pollutant</th>
<th>Emissions (kg·yr(^{-1}))</th>
<th>VAR1</th>
<th>VAR2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carbon dioxide</td>
<td>110.0</td>
<td>1,590.0</td>
<td></td>
</tr>
<tr>
<td>Carbon monoxide</td>
<td>0.471</td>
<td>6.8</td>
<td></td>
</tr>
<tr>
<td>Unburned hydrocarbons</td>
<td>0.0522</td>
<td>0.753</td>
<td></td>
</tr>
<tr>
<td>Particulate matter</td>
<td>0.0355</td>
<td>0.512</td>
<td></td>
</tr>
<tr>
<td>Sulphur dioxide</td>
<td>0.238</td>
<td>3.44</td>
<td></td>
</tr>
<tr>
<td>Nitrogen oxides</td>
<td>4.21</td>
<td>60.6</td>
<td></td>
</tr>
</tbody>
</table>

The Emissions Table 15 of the simulation results demonstrate the total amount of each pollutant produced annually by the Off-Grid system. The pollutants originate from the consumption of fuel and biomass in generators, the boiler, and the reformer, as well as from the consumption of grid power, if present. There is an option to sell the surplus of energy to the grid, e.g. in case of a Micro-Grid or Smart-Grid solution. The system can even achieve negative emissions of one or more pollutants if it sells a low-emissions electricity to the grid.

In conclusion, one of the very important tasks of the ADSM is currently minimize the cost of the battery capacity and the size of the installed power of photovoltaic panels. Optimization of the operation using the ADSM assumes a significant reduction of these investment costs. The RESs could decrease the pollutant production to minimal values and this will be helpful especially in the heavy industrial districts/regions, where e.g. during winter season are several times announced the “SMOG” situation, such as in our Moravian-Silesian region in Czech Republic.
6. ADSM VERIFICATION USING PRACTICAL EXPERIMENTS

The ADSM concept as well as the entire platform of the Off-Grid system was evaluated using practical experiments. The results from these specific practical experiments are compared with the computer simulation in this chapter to verify the developed algorithm and entire concept of AEU.

The year-round actual operating conditions of the Off-Grid system operated under the ADSM have been used. Over these 12 months have been used the complete laboratory equipment – appliances and both power sources PV and WPP. I compared the actual obtained data from the measuring system and from the ADSM log file with the computer simulations in order to obtain the differences between the systems operated with ADSM and without ADSM and even between the systems operated exclusively with PV and with PV and WPP.

6.1. The Active energy unit verification

The developed physical platform of AEU in university campus is primary intended for testing and research and development. Based on the real data and simulated operation of AEU is carry out the evaluation and verification of the proposed ADSM. Fig. 29 shows the technical background of the real-operated AEU platform.
All the results are obtained using practical experiments and are compared with the computer simulations. Data used in the simulations are the same like in the database of measured values for the given time period (year 2014).

The work of the AEU is compared with and without ADSM in Fig. 30. You can see details from May (from 2014/05/15 to 2014/05/20) where I compare the systems. The system operated under ADSM can use the available energy better based on the inputs which corresponds with the longer time of the comfort usage duration, i.e. there are no time periods where the appliance cycle is postponed or removed. I tested the behaviour of the AEU with ADSM each month of the year when both energy sources were used and when only the photovoltaic power plant was used. The computer simulation was carried out for the same months and the results were compared in the following Table 16. The following table depict the results for each month with and without the wind power plant and with and without the ADSM. The features evaluated in my experiments and depicted in the table are: “Missing Energy” is the sum of energy which was missed in the entire system during the time interval. “Differences” are the proportional differences between the Off-Grid system operated without ADSM and with ADSM. The term “Missing Energy” is used for the energy which comes from the LPG generator in the worst case, when the battery bank is discharged and the renewable power sources are powerless. This additional source serves as a “back up” energy source to maintain fresh food, thermal comfort, etc. It should be noted that the following tables present achieved results of AEU operation in comparison with a computer simulation.
### Table 16 Annual data of ADSM evaluation and comparison in AEU platform

<table>
<thead>
<tr>
<th>Month</th>
<th>PV only a</th>
<th>PV and WPP b</th>
<th>PV only a</th>
<th>PV and WPP b</th>
<th>PV only a</th>
<th>PV and WPP b</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>With ADSM a</td>
<td>Without ADSM a</td>
<td>Differences (%)</td>
<td>With ADSM b</td>
<td>Without ADSM b</td>
<td>Differences (%)</td>
</tr>
<tr>
<td>January</td>
<td>333</td>
<td>512</td>
<td>35</td>
<td>197</td>
<td>311</td>
<td>37</td>
</tr>
<tr>
<td>February</td>
<td>374</td>
<td>524</td>
<td>29</td>
<td>219</td>
<td>356</td>
<td>38</td>
</tr>
<tr>
<td>March</td>
<td>342</td>
<td>474</td>
<td>28</td>
<td>132</td>
<td>298</td>
<td>56</td>
</tr>
<tr>
<td>April</td>
<td>189</td>
<td>297</td>
<td>36</td>
<td>72</td>
<td>149</td>
<td>52</td>
</tr>
<tr>
<td>May</td>
<td>155</td>
<td>234</td>
<td>34</td>
<td>9</td>
<td>92</td>
<td>90</td>
</tr>
<tr>
<td>June</td>
<td>67</td>
<td>157</td>
<td>57</td>
<td>0</td>
<td>47</td>
<td>100</td>
</tr>
<tr>
<td>July</td>
<td>82</td>
<td>197</td>
<td>58</td>
<td>11</td>
<td>72</td>
<td>85</td>
</tr>
<tr>
<td>August</td>
<td>106</td>
<td>209</td>
<td>49</td>
<td>17</td>
<td>96</td>
<td>82</td>
</tr>
<tr>
<td>September</td>
<td>113</td>
<td>221</td>
<td>49</td>
<td>67</td>
<td>108</td>
<td>38</td>
</tr>
<tr>
<td>October</td>
<td>141</td>
<td>215</td>
<td>34</td>
<td>72</td>
<td>104</td>
<td>31</td>
</tr>
<tr>
<td>November</td>
<td>279</td>
<td>399</td>
<td>30</td>
<td>145</td>
<td>228</td>
<td>36</td>
</tr>
<tr>
<td>December</td>
<td>569</td>
<td>745</td>
<td>24</td>
<td>268</td>
<td>383</td>
<td>30</td>
</tr>
<tr>
<td>Total</td>
<td>2,750</td>
<td>4,184</td>
<td>34</td>
<td>1,209</td>
<td>2,244</td>
<td>46</td>
</tr>
</tbody>
</table>

a - Computer simulation results  
b - Results obtained from practical experiment (measuring system)

As the examples of the simulation results can serve two selected months – June and December. Those two months represent the extremely differences between power production from RESs during the year.

The 1st month considered in this comparison is June. In this month is expected that the solar irradiance will be high during the day and, therefore, the photovoltaic power plants will generate
the power extremely close to the maximum limit of the installed power. The wind power plant will generate the energy as well because the wind is always present.

The 2nd month considered was December. The winter season means that the power production of the wind power plant is higher than in summer, but the photovoltaic will contend with a lack of the solar irradiation. The appliances scheduled for the summer and winter are also slightly differ. This is primarily due to the fact that the heating in the summer is replaced by the air conditioning (different power input and time scheduling). The other appliances may be very similar. The precise list of appliances is depicted with their parameters in Table 7. The length of one period was set at 5 min. The primary goal of the platform of the ADSM is to maintain the system without a need of energy from the external grid, thereby in the true Off-Grid mode. I will therefore evaluate the properties of the designed model and platform which will demonstrate the ability of the algorithm to improve the comfort of the living as well as to reduce the power consumptions or decrease the price of the platform with cheaper/smaller batteries or smaller power plants.

In the case of the month of June, Table 16, when the system was only powered by PV, the difference between the option with and without ADSM was 57 %. In the other cases, when both renewable resources were present the time period with a lack of energy using the ADSM was not recorded. The system has been managed in fact with the electric energy with no deficit during June. The results, with PV only option, indicate that the ADSM is able to reschedule the appliance cycles in a way that the total amount of missed energy is significantly lower, it is about 67 kW·h compared to 157 kW·h without ADSM. A different situation is when both power plants are used. The system with ADSM works without any problem and all the appliance cycles are performed. The system without ADSM is not able to perform all the cycles and more than 47 kW·h of the energy is missing.

The situation in the month of December, see details in Table 16, is completely different, since this is the month when the intensity of the solar irradiation is extremely low. The maximum value is about 300 W·m\(^{-2}\), but the average wind speed is around 5 m·s\(^{-1}\). The option with ADSM compared to the option without ADSM saves up to 24 % of the electricity in the case of an installation with only the PV. In the case of PV and WPP it is actually 30 %. It should be noted that the system cannot reschedule the appliances somewhere else in time, when available energy from RESs in entire month is extremely low.
The above interpreted results correspond with the original idea about the electricity savings. The ADSM is able to significantly reduce the amount of missing energy in the system and can better manage with the available energy in comparison with the system without the ADSM. This argument is well-founded by the achieved results in Fig. 31. The next step in the evolution of this sophisticated dispatcher management system is its refinement of inputs in the form of increasing the accuracy of forecasting of electrical power production, shortening the computational intervals, decrease the LGP Generator run time, etc., which will contribute to the overall increase in the usefulness and effectiveness of the system.

As you can see from Fig. 31, the system benefit lies in the energy managing during the time and number of sources. Because more sources means in this case better managing of available energy.
7. CONCLUSION & DISCUSSION

This doctoral thesis presents a novel method and approach for the Active Demand Side Management (ADSM) in real-operated Off-Grid system operated in a Smart-Grid environment. This proposed method combines artificial intelligence methods along with deterministic algorithms in cooperation with software and hardware parts to complete the Active Energy Unit (AEU). The Off-Grid system operated under the ADSM can significantly reduce the power outage due to intelligent scheduling.

The developed intelligent ADSM system recommends the users the consumption plan which is based on the database of the operating conditions, consumption analysis, battery bank state of charge, information from monitoring system, the relevant meteorological forecasts and energy forecast from renewable sources. The entire control system recommends and manage the power circuits or individual appliance according to the developed algorithm. Nevertheless, the users are informed about the current status of the system and have an option to change the status of individual appliances/circuits in real time, if needed.

The practical and simulation results are presented in this doctoral thesis based on actual weather conditions, power consumptions, etc. and demonstrate that the proposed ADSM is able to intelligently spread out the energy requirements during the day to achieve the maximum living comfort while the energy independence is guaranteed.

Using the proposed ADSM algorithm, the AEU is able to solve the lack of energy during the energy peaks, shift the loads in time, increase the loads or even fill up the valley when the power production is predominately increases over the consumption. In addition, the proposed ADSM further increases the RES efficiency and reliability, maximizes the self-consumption at an appropriate time, and shortens investments costs with lesser energy payback time.

In the case of commercialization of this unique system from the test environment to the commercial realm, it can be reached the self-sufficiency of any object – from households to Off-Grid communities up to the micro-regions using the ADSM inputs/outputs modification. Therefore, the current energy policy has to be collectively adjusted to prevent the abuses over the World. The building-up of the technological background for the commercialization of AEU would include the creation of new jobs, with an emphasis on local conditions - the reduction of unemployment in the
regions where it is most needed. The part of the financial profit would be invested back into the regional development and the necessary infrastructure. The investment costs of energy storage and the size of installed electric sources can be significantly reduced using optimized operation with ADSM, at the same time the ADSM minimize the impact of supplementary source(s). As an example of the positive environmental benefits of the AEU can be mentioned the significant reduction in the harmful pollutants production, especially in industrial regions that suffer from SMOG situation and pollutants overproduction. To realize this, it would be achieved the improving the quality of the environment in the most critical regions for keeping the landscapes for next generation.

ADSM can be understood in a wider sphere as a basic tool for managing energy flows within modern intelligence networks, so-called Smart-Grids. In case of the application ADSM in Off-Grid systems there is a need, however, to expand the computational core of ADSM with a tool which will also provide (i) parameters for quality electric energy within established limits and (ii) a safe and reliable functioning of the Off-Grid in relation to the concept of protection. The provision of the parameters of quality electric energy is essential for proper functioning of appliances. The concept of protection has to ensure the safe and reliable operations of the Off-Grid system both in terms of the equipment and in terms of the person living in the given Off-Grid system. The development of these kinds of tools is a major challenge at present as there is a need to ensure its functionality in the specific conditions of the Off-Grid system which is marked by a time change of a short-circuit power and a multiple lower value with the On-Grid systems. Both mentioned tools are being developed and tested at present.

The actual ADSM algorithm can also be used after relevant adaptations for managing the micro-region with more tools and with various appliances. The management of the micro-region can be presented with a model example. In the same fashion as with a residence, ADSM can manage energy flows, not of course by means of individual appliances but through entire energy objects. These objects, in the same fashion as appliances, will have various predictable characters of consumption and various priorities, for example, “0” will have a hospital, “1” production facilities, “2” offices and “3” particular households. Another support tool such as Electromobility will be serve, apart from providing transport, as another source of electric energy when there is a lack or in contrast as an accumulation instrument when there is an excess.
7.1. Contributions of this doctoral thesis

The following points summarize the highlights of my scientific and research contributions:

- A universal algorithm has been developed to control the power flows inside the energy units
- An innovate solutions has been applied using artificial intelligence techniques
- Pilot testing and practical verification has been validated
- A Heuristic approach for Active Demand Side Management system (ADSM) has been developed
- Achieved results make prerequisite for new development of leading-edge power distribution systems in a Smart-Grid environment
- ADSM has been developed with a comprehensive approach to all aspects of sustainable energy development.

The following points summarize the highlights of my industry contributions:

- The ADSM model is verified by conducting a long-time operation
- Efficiency and reliability of Renewable energy sources has been enhanced
- The proposed ADSM reduces the power consumption and decreases the energy platforms’ price.
- Active energy unit is suitable solution for using as a basic cell of Smart-Grids
- Energy, economic and environmental aspects with social impact has been defined
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Publishing activities & Projects participations

Journals with impact factor


Journals with impact factor (under review)


Journals – indexed in Scopus


Conference proceedings – indexed in Web of Science


**Conference proceedings – indexed in Web of Science (Accepted, conference proceedings in process)**


Conference proceedings – indexed in Scopus


Conference proceedings – indexed in Scopus (Accepted, conference proceedings in progress)


Conference proceedings – non-indexed


Invited Presentation

In the framework of the project LE13011 Creation of a PROGRES 3 Consortium Office to Support Cross-Border Cooperation and project InterEnergy (CZ.1.07/2.3.00/20.0075).

- New development direction in Off-Grid systems, University of Žilina, Žilina, 12. 12. 2013, Slovakia
- Active control system for energy units using soft-computing methods, University of Žilina, Žilina, 29. 10. 2014, Slovakia


- Development in Off-Grid and Smart Grid Area

Prototype

Stuchlý Jindřich; Prokop Lukáš; Mišák Stanislav; Vramba Jakub: Stacionární monitorovací systém pro diagnostiku akumulačních zařízení pro ostrovní provoz

Software:

Stuchlý Jindřich; Prokop Lukáš; Mišák Stanislav; Vramba Jakub: Software pro analýzu provozních stavů energetických jednotek.
Project participation:

Solved projects:

SP2012/53 Monitorovací a ovládací systém Energeticky soběstačného "SMART" domu
SP2013/68 Vývoj SMART systému řízení energeticky soběstačného domu
SP2014/49 SMART Energetická koncepce pro administrativní budovu

Projects in process:

SP2015/170 Vývoj detektoru poruch izolačních systémů s podporou databázových systémů
SP2015/178 Vývoj koncepce řízení aktivní inteligentní sítě
Project LE13011: Creation of a PROGRES 3 Consortium Office to Support Cross-Border Cooperation and project InterEnergy (CZ.1.07/2.3.00/20.0075).
CZ.1.05/2.1.00/03.0069 – ENET – Energetické jednotky pro využití netradičních zdrojů energie
Project 22420320024 – Vytvoření informačního portálu na zvýšení povědomí příhraničí v oblasti inteligentních elektrických sítí
TAČR: TH01020426 – Systém pro aktivní řízení decentralizovaných energetických jednotek na lokální úrovni
PRE-SEED: Technologie pro řízení malých energetických jednotek