D6.6.21: A Prototype of an Intelligent Decision-making Component for Smart Grids

Description of the Simulation Model for the Microgrid's Energy Management System

Revision History

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Abstract

This deliverable continues the work described in deliverable D6.12.7 “Survey Report on KPIs for the Control and Management of Smart Grids”, which was made during the 2nd funding period of SGEM-project as part of WP6. In D6.12.7, an idea of a microgrid with an Energy Management System (EMS) was introduced and defined. Focus of this deliverable is on the implementation of the microgrid EMS simulation model. The simulation model is implemented on Matlab® and Simulink® software environments. The top-level simulation model includes blocks for Microgrid Control Centre (MGCC), local power generation, energy storages, loads and power distribution. There are four technologies used for power generation in the microgrid: hydroelectric, photovoltaic, wind and diesel power generators. Load in the microgrid consists of single-family houses with electric heating. Load and generated power depend on a number of parameters. For example, time of day and outside temperature. The motivation for making this simulation model is to calculate the benefits of forming microgrids in Finland.

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1 Preface

This report was done as a part of the Finnish national research project "Smart Grid and Energy Market" SGEM Phase 3 and it was funded by Tekes – the Finnish Funding Agency for Technology and Innovation and the project partners.

2 Introduction

This is a follow-up report to deliverable D6.12.7 “Survey Report on KPIs for the Control and Management of Smart Grids”, written as part of SGEM project’s funding period 2. In that deliverable, the concept of smart grids and especially microgrids was introduced. The focus of that deliverable was to introduce the concept of the microgrid Energy Management System (EMS). The purpose of the EMS is to make decisions regarding the best use of the loads, storage units and generators for producing electric power and heat in the microgrid. This deliverable documents the implementation of a microgrid EMS simulator on Simulink® and Matlab® software environments.

The power generation technologies in the simulation model were selected to favor renewable energy sources (RES). This is why gas and coal (or nuclear) power plants are not considered. Photovoltaic, hydroelectric and wind power generators have been modeled in the simulation. There is also a model for a diesel generator, which is used mainly (due to its fuel cost) for emergency power supply. The generators in the simulation model produce only electricity. If we want to add heat production to the microgrid, we could add a model for a biogas and a peat generator. Loads in the microgrid are single-family houses, whose power demands vary with time of day and year. The houses use electric heating.

This version of the document and the simulation model omits feed-in-tariffs. Wikipedia defines a feed-in-tariff (FIT) as “a policy mechanism designed to accelerate investment in renewable energy technologies. It achieves this by offering long-term contracts to renewable energy producers, typically based on the cost of generation of each technology.” By using feed-in-tariffs in cost calculations, it would be easy to show that microgrids with wind power generators are a profitable investment even in Finland. Germany offers FIT compensations that are more generous for solar power producers. If the German FIT model were used in Finland, also solar power investments would be profitable. Now Finland has feed-in-tariffs for wind power, biogas and peat. This document and simulation model also omits emission trading and its possible effect on the price of electricity.

3 Microgrid Simulation Model

A top-level simulation model shown in figure 1 has been developed for the simulation of the microgrid EMS using Simulink software. With Simulink, we can model the microgrid with a number of blocks, each performing a distinct function. Simulink models the signals traveling between the blocks and the simulation can be thought of as a discrete-time process. The timescale for the simulation is one year with 1-hour resolution. The power unit used is kilowatt [kW] so the model bases the energy calculations in kWh. Simulink is closely related to Matlab environment and we have exploited this by performing more sophisticated tasks as regular Matlab functions inside the Simulink blocks. The blocks in the simulation model process their input signals every simulation time resolution, after which the new signals are sent to the next block. In the new blocks, the signals are once again processed when the next simulation time resolution has passed. There is no delay in sending signals between blocks.

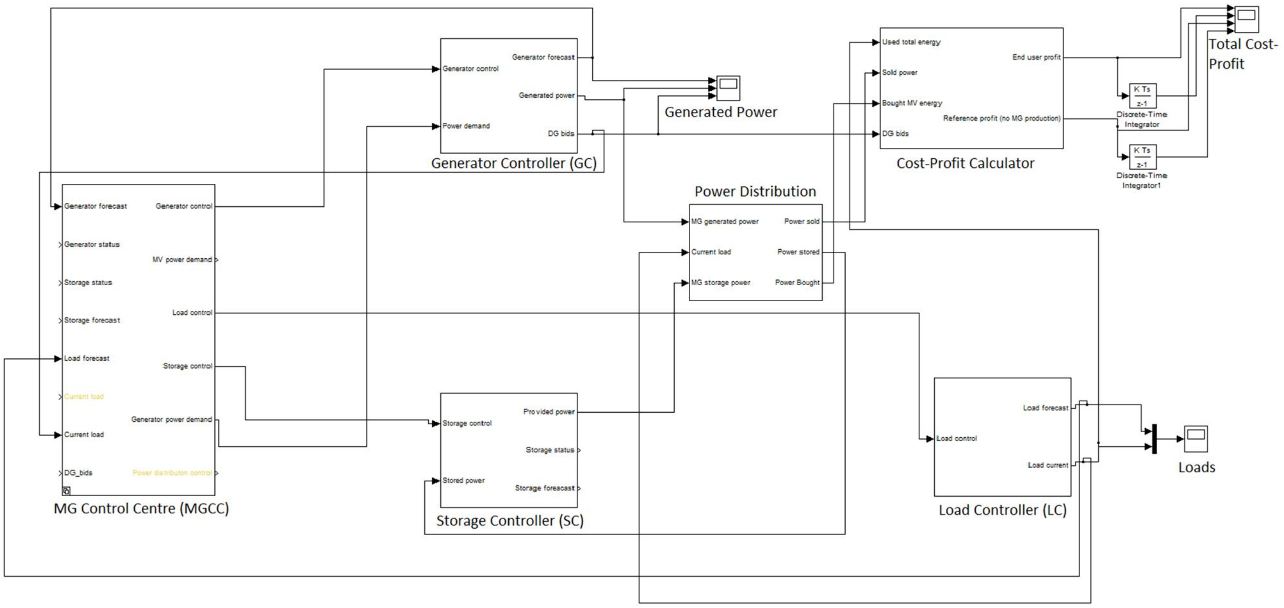

Figure 1. Top-level Simulation Model

In the top-level simulation model, the functionality has been spread among six blocks: Microgrid Control Centre (MGCC), Generator Controller (GC), Load Controller (LC), Storage Controller (SC), Power Distribution and Cost-Profit Calculator. The three smaller blocks, Generated Power, Loads and Total Cost-Profit, are used for generating graphs and saving results while the simulation is running. Before going into individual blocks in chapter 5, we will introduce the different control policies available for the EMS.

4 Energy Management System (EMS) Control Policies

An EMS is a system where the MGCC controls the resources of a microgrid according to some (market) policies. MGCC should act automatically and in an optimal way. However, in this implementation version of the simulator the functionality of the EMS has been divided among three blocks in the simulation model. These blocks are MGCC, Power Distribution and Cost-Profit

Calculator. The EMS policies were defined in deliverable D6.12.7 [14] but the main points are given in the next three chapters as a reminder. Policy A is called the Good Citizen policy, policy B is called the 'Ideal Citizen' policy and policy C is called the Green policy. In addition, we need a reference case for comparison.

4.1 Reference Case

A reference case is needed to find out if the proposed policy controlled EMS for the microgrid is better than the present-day situation. In addition, it helps in comparing the goodness of each policy. The reference case refers to a present-day situation where each customer in e.g. a suburb acts as an individual. The suburb has no local generation, no energy storages and no MGCC. All customers satisfy their power demand by buying electricity directly from the Distribution System Operator (DSO) at the currently offered price. With this simulator, we can calculate the total sum of each customer's electricity bill over a single year. The reference case can then be compared to a case where the same customers would set up a microgrid and have their own power generation, storages and an automated MGCC with an EMS. By using the same price data as in the reference case, each customer's electricity bill should be lower.

4.2 Policy A: Good Citizen

In the good citizen policy, the MGCC aims to satisfy the total energy demand of the microgrid by using its local production as much as possible, without exporting power to the distribution grid. That is, the energy self-sufficiency of the microgrid is maximized. From the consumer's point of view, the MGCC minimizes the operational costs of the microgrid, by taking into account open market prices, demand and DG bids. The consumers of the microgrid share the benefits of the reduced operational costs [14].

The function to minimize for each simulation time interval is: *Minimize{cost}*, where

$$cost = \sum_{i=1}^{N} DG\_bid(x_i) + \sum_{l=1}^{M} storage\_bid(z_l) + AX + \sum_{j=1}^{K} load\_bid(y_j) \quad (1)$$

The constraints for this minimization function are:

1. Technical limits of the DG sources and storages
2. Power balance (2) of the microgrid

$$P\_demand = X + \sum_{i=1}^{N} x_i \pm \sum_{l=1}^{M} z_l - \sum_{j=1}^{K} y_j = 0 \quad (2)$$

4.2.1 Implementation of Policy A

The implementation of the good citizen policy can be made simpler if the logic of the policy is realized with simple rules, instead of solving an optimization problem. In the following are the rules for different components.

Control of generation & load components

- Satisfy demand from loads with local generation
- If still demand > generation, check if there is power in the storage components
- If no power left in storage:

- If demand is urgent, buy power from distribution grid
- If demand is not urgent, offer to satisfy demand at a later time

Control of storage components

- If generation > demand, after all demand is satisfied, store power into storage components
- If there are two types of storage components with fast and slow reaction times, fill the fast storage units first. If fast storage is full, start filling slow storages.
  - Fast storages can satisfy demand right away
  - Slow storages take a couple of hours to discharge. These can be used for non-urgent demand
- Amount of power in storage components should diminish as a function of time (storage loss). Fast storages should lose power faster than slow storages.

However, good citizen policy has not been implemented in the simulation model.

4.3 Policy B: Ideal Citizen

In the ideal citizen policy, the MGCC maximizes the profit gained from power exchange with the upstream network. The MGCC sells energy to the consumers of the microgrid and sells the excess production from the DG sources to the DSO at the market price. If the power produced by the DG sources is not enough or too expensive to cover local demand, power is bought from the upstream network and sold to the consumers [14].

In this policy, the optimization function for each simulation time interval is,

Maximize{revenue-expenses} = Maximize{profit}

$$revenue = AX + A\sum_{i=1}^{N} x_i \pm A\sum_{l=1}^{M} z_l \quad (3)$$

$$expenses = \sum_{i=1}^{N} DG\_bid(x_i) + \sum_{l=1}^{M} storage\_bid(z_l) + AX + \sum_{j=1}^{K} load\_bid(y_j) \quad (4)$$

And finally,

$$profit = A\sum_{i=1}^{N} x_i \pm A\sum_{l=1}^{M} z_l - \sum_{i=1}^{N} DG_{bid(x_i)} - \sum_{l=1}^{M} storage\_bid(z_l) - \sum_{j=1}^{K} load\_bid(y_j) \quad (5)$$

The constraints for this maximization problem are:

1. Technical limits of generators and storages
2. Minimum demand that must be met in the microgrid, which must satisfy

$$P\_demand \leq X + \sum_{i=1}^{N} x_i \pm \sum_{l=1}^{M} z_l - \sum_{j=1}^{K} y_j \geq 0 \quad (6)$$

4.3.1 Implementation of Policy B

As with policy A, the functionality of this policy can be implemented with simple rules, instead of solving the formulas chapter 4.3.

Control of generation components

- Locally generated power is exported if "selling price" > "cost of generation"
- If "cost of generation" < "buying price" use the locally generated power to satisfy local demand
- If "cost of generation" < "buying price" and all demand is satisfied -> store power into storage components

Control of load & storage components

- Satisfy demand bids with power from storage components (1st priority)
    - o If demand is urgent use fast storage
    - o If demand can wait, use slow storage
- If storages are empty, use locally generated power if available (2nd priority)
- If no local generation available, buy power from distribution grid (3rd priority)
- Amount of power in storage components should diminish as a function of time (storage loss)

In the simulation model, policy B has been implemented by using these rules. The functionality of this policy is divided into three blocks: MGCC, Power Distribution and Cost-Profit Calculator.

4.4 Policy C: Green Policy

In this policy, the optimization is done to maximize the use of RES generation components. This means, that the optimization formula needs to minimize the carbon footprint of power generation [14].

The optimization function for this policy is,

Minimize{carbon_footprint_cost}, where

$$carbon\_footprint\_cost = C_1 * X + \sum_{i=1}^{N_1} C_2 * RES\_x_i + \sum_{j=1}^{N_2} C_3 * TRA\_x_j \tag{7}$$

Constraints for this minimization function are the technical constraints of generation units and the power balance in the microgrid.

$$P\_demand = X + \sum_{i=1}^{N} x_i \pm \sum_{l=1}^{M} z_l - \sum_{j=1}^{K} y_j = 0 \tag{8}$$

4.4.1 Implementation of Policy C

Green policy has not been implemented in the simulation model.

5 Microgrid Control Centre (MGCC)

Figure 2 depicts the Simulink model for the MGCC. The inputs in use are:

- Sell to MV price: Price for selling power to the DSO
- Buy from MV price: Price of bought power from DSO
- DG cost: Total cost of locally generated power
- Load forecast: The predicted load for the next hour

Outputs of this block are:

- Generator control: This signal commands the generators to switch power production on/off
- Storage control: Signal to switch power storages on/off
- Load control: Signal to switch loads on/off
- Generator power demand: The amount of power needed from generation components
- MV power demand: The amount of power that needs to be bought from outside microgrid

The functionality of the MGCC is defined in a Matlab function. At the moment the MGCC implements policy B (Ideal citizen). Wind, Photovoltaic and Hydroelectric generators are run at full power if:

1. Power is cheaper to produce locally than to buy from the DSO
2. Power can be sold to the DSO at a profit

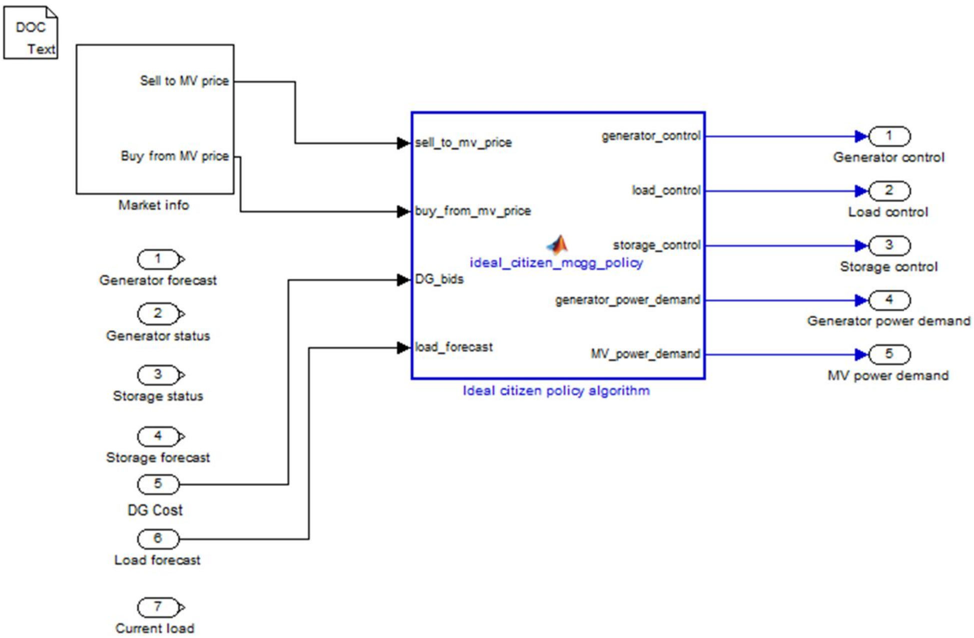

Figure 2. MG Control Centre block

Diesel generator is run if it is profitable. This if-clause makes it very rare that the diesel generator is turned on because in our simulations the microgrid is always connected to the upstream network (i.e. island operation is not simulated).

6 Power Distribution

The power distribution block is used to distribute generated and purchased power to microgrids load and storage blocks. Figure 3 depicts the Simulink model of the block. This block implements a part of the functionality of the ideal citizen policy.

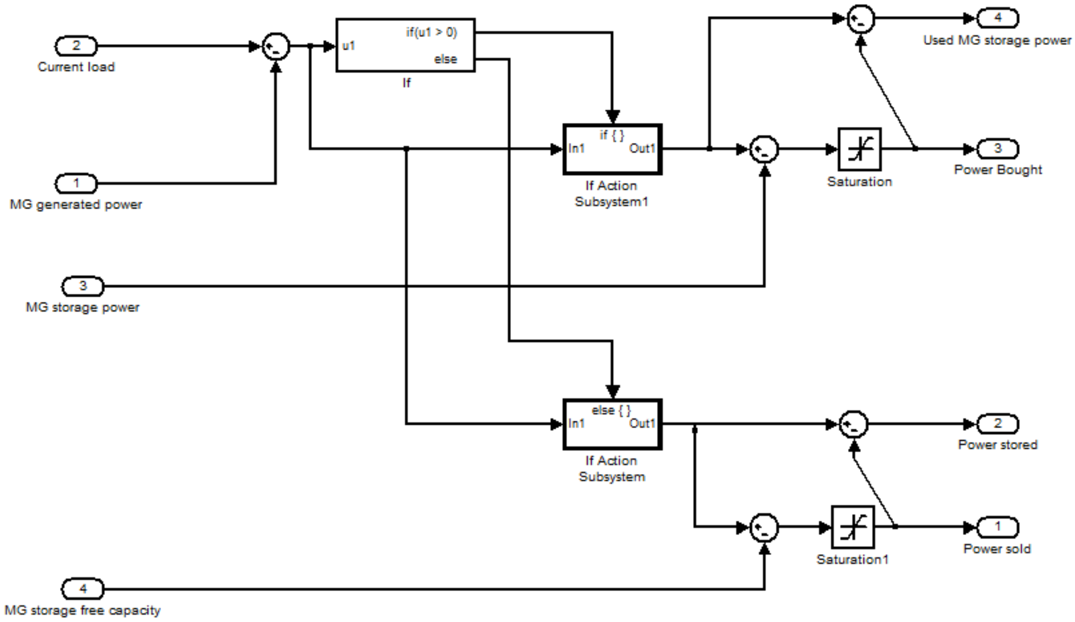

Figure 3. Power Distribution block

The inputs for this block are:

- Current load: Current total power demand (load) of the microgrid
- MG generated power: Power available from the generation components
- MG storage power: Power available in storage
- MG storage free capacity: Free capacity of battery

Output signals of the block are:

- Used MG storage power: How much stored power is used
- Power bought: How much power must be bought from the DSO
- Power Sold: How much power can be sold
- Power Stored: How much power is put into storage

This block calculates if the microgrid needs to buy energy from the DSO or if it can sell excess energy. If the local generation can produce more power than the loads require, the excess energy is calculated and sold. If the loads require more power than the local generators can produce, the difference must be bought from DSO so that all loads are satisfied. If energy storages are used, excess energy is used to fill them up before it is sold.

7 Cost-Profit Calculator

This block calculates the profits gained from using the ideal citizen policy as the guideline for the EMS. The electricity bill with the ideal citizen policy is compared to the bill with the reference case. The data for the price of buying and selling electricity is from Nord Pool (the Scandinavian power exchange). We used the hourly Elspot prices for Finland in the year 2011. Elspot is a market where physical kilowatt-hours are traded in the same manner as shares are traded on a stock exchange.

The inputs for this block are:

- Sold power: output from the power distribution block
- Sell to / Buy from MV price: Hourly prices for dealing with the DSO [Nord Pool Spot]
- Bought MV energy: 'power bought' output signal from the power distribution block
- Used total energy: Current load demand of the microgrid
- DG cost: Total cost of locally generated power

The outputs of this block are:

- End user profit: Calculates the profit gained from selling power to the DSO
- Reference profit: Electricity bill of the reference case

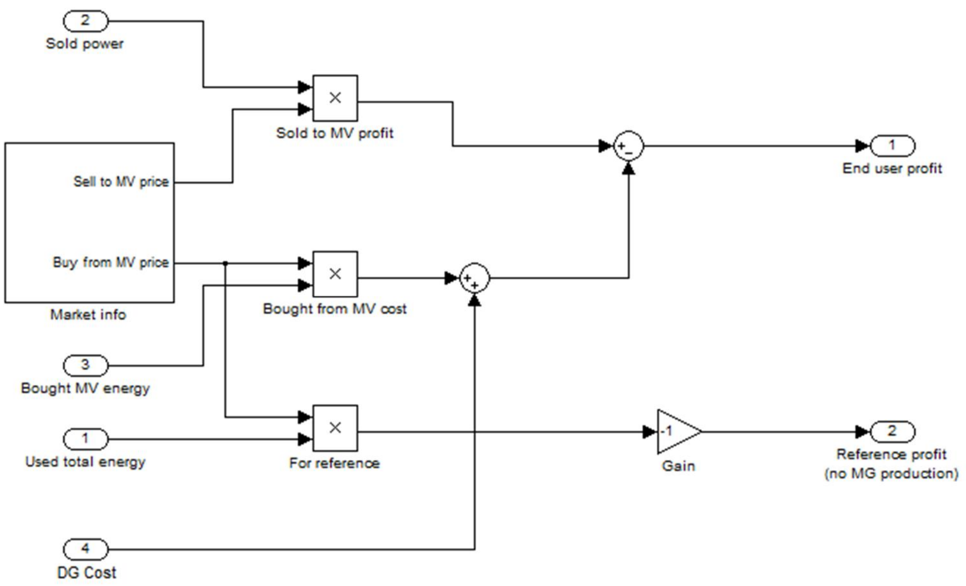

Figure 4. Cost-Profit Calculator block

8 Generator Controller

Simulations cover several different technologies, which are currently available for microgrids to generate electrical energy. One example of each generator type is introduced here, but the simulation functions can simulate any device of its type, if the system's detailed technical specifications are at hand. The selected devices present small-scale generators, which are currently available for microgrids. Gas, peat or coal are not potential options for microgrid systems in Finland.

Weather and other environmental conditions are used as monthly or daily average to keep the simulation functions simple.

The costs of energy generation systems vary in a very wide scale. Therefore, the costs model is a suggestion and other costs model can be used.

8.1 The Simulated Devices and Their Environment

The calculated energy bids are always bids for one (1) hour in kilowatts [kWh].

Each function simulates one energy generation unit of its type, which means that the nominal capacity of one bid varies from 0.29 kW to 1000 kW.

Table 1 explains the details of the energy generators simulated with Matlab. Only one generator of its type is simulated. Number of energy generation units utilized in simulation can vary with a wide scale. The output power of each generator type includes system losses; the given power is the input power delivered to the microgrid. Efficiency of power generation systems is not shown as only the diesel engines produce surplus heat, which could be utilized in heating. The selected brands and models of the devices to simulate are typical examples of widely used systems.

Table 1. The simulated generators

GENERATOR TYPE	Brand / model	Nominal electrical power of one unit	Minimum limit for the power	Maximum limit for the power (one unit)
Wind turbine	WinWinD WWD-1	1000 kW	25 kW	1000 kW
Solar panel	Suntech's Pluto 290	0.29 kW	0.1 kW	0.3 kW
Hydroelectric generator	-	400 kW	330 kW	790 kW
Diesel engine	Wärtsilä 32	1026 kW	100 kW	1026 kW

Weather information is always average per month, in two weeks periods or per day and it is implemented in the source code as Matlab's tables. Number of day from 1st of January onwards and time of day as hours (0-23) are used for input. Table 2 illustrates more details of weather information.

Table 2. The average weather information used

Weather parameter	Unit	Location	Source of information
Monthly average temperature	Cº	Oulu region, Finland	Finnish Meteorological Institute

Average monthly wind speeds	m/s	Oulu region, Finland	Finnish wind Atlas
Intensity of Solar irradiation	W/m^2	Oulu region, Finland	Calculated with APROS simulation software
Flow rate of water	m^3/s	Flow rates of Tolpankoski river at Oulainen, Finland	www.environment.fi

8.2 Storage Systems for Energy

Energy could be stored in microgrids with flywheels, super capacitors for controlling quick changes in power balance. Energy can be stored for longer term with batteries, pumped storages or compressed air. We analyze only the costs of the battery options in this report.

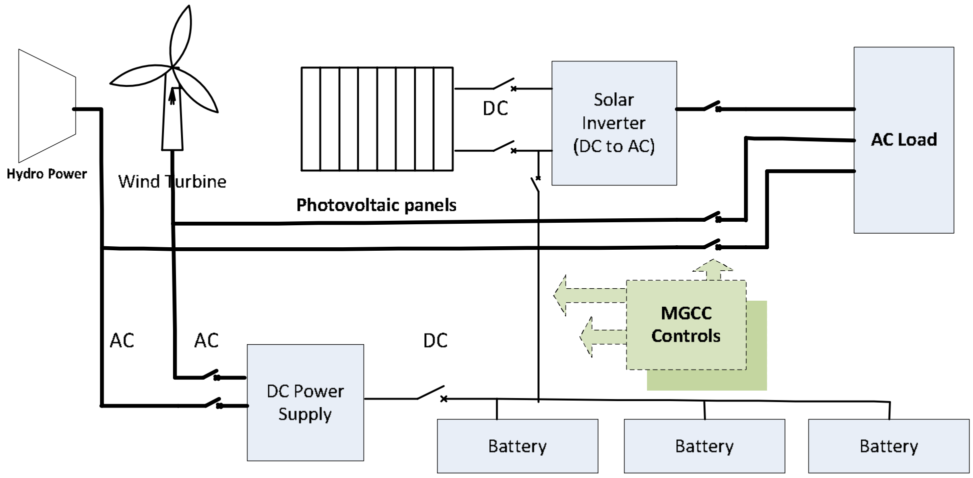

Figure 5. A simplified view of the main devices required to store the energy which is generated in a microgrid

Deep-cycle batteries are generally recommended for solar-powered systems. They tolerate discharging deeply many times with minimal loss of capacity, providing a small current, which lasts a long time. Their purchase price is higher but lifetime costs are lower. Still their capacity reduces to about 60% in their lifetime and storage losses increase with age, both depending strongly of their use.

Table 3. The simulated energy storage systems

DEVICE TYPE	Brand/model	Capacity of one unit	Voltage	Current rate	Output power	Storage loss
Deep-cycle	Rolls Series	475-500 Ah	12 V	5-7 A	60 - 80 W	

battery	5000	(6 kWh at 5 amps, 5.7 kWh at 6.6 amps)				
Battery Bank	Rolls/Surrette	1600 Ah 76,8 kWh	48V	30 A	1.6 kW	

An AC/DC converter (rectifier) or a DC power supply is required in a storage system to convert the AC power generated by the wind turbines and the hydro power plant to DC for the batteries.

Solar inverters are specific versions of inverters designed especially for solar panel systems. A solar inverter may provide a MPPT, which increases produced photovoltaic energy with 20-30%. The inverter also converts the stored DC energy to AC.

A typical peak load of a one-family house without electric heating in Finland is less than 1 kW. If we assume that peak power requirement is 2 kW for each house in the microgrid, then 100 consumers need a system of 200 kW. Most small-scale inverters produce less than 20 kW while the next level is at 100 kW.

Table 4. The devices for the energy storage systems

DEVICE TYPE	Brand/model	Input Voltage	Current rate	Output power	Efficiency
Small-scale Solar Inverter	Danfoss TripleLinx TLX +15KW	1000 V (max DC input) 250V (minimum input)	Max DC input: 3x12A	15 kW	98%
Central Solar Inverter	CHNT Power CPS SC100KT	600 V/dc	350 A	100 kW	96.6%
Central Solar Inverter	Power-One PVI-CENTRAL-250-US-480 250 kW Inverter	600 V/dc	850 A	250 kW	97.2%
Central Solar Inverter	ABB PVS800	450-750 V/dc	600 A	250 kW	97.5%

AC/DC Converter (Power Supply)	Magna-Power DC Power Supply	480 V/ac	54 A(ac)	30 kW	86%
AC/DC Converter (Power Supply)	Magna-Power DC Power Supply	480 V/ac	135 A(ac)	75 kW	88%

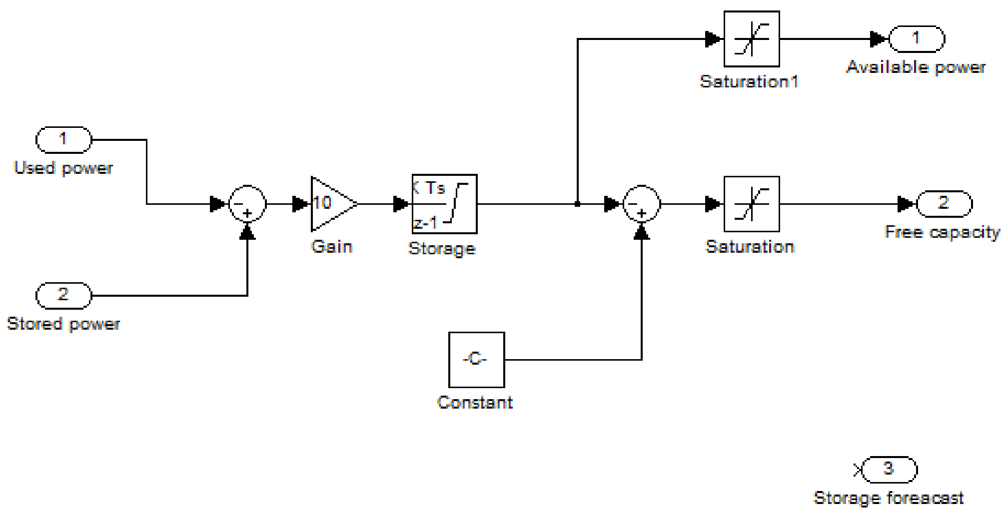

Figure 6. Simulation model for storage components

8.3 The Costs Model

The recent reports [1] [2] provide a cost comparison between different methods of energy production in Finland. The large commercial systems that were analyzed in [1] are always much more productive than the micro systems, but their cost model is rather similar. We shared the total costs of producing energy to four parts:

- investments
- operation and maintenance
- fuel
- emissions trading

We neglect the costs of emissions trading (CO_2 costs) in the simulation of the microgrid systems, although they have an essential role in the energy production today. Costs of transmission investments are included in the investment costs of the generators.

The costs of energy storage systems cover only the investment costs as operation and maintenance costs are minor and active use of the storage system do not change those low costs.

8.3.1 The Costs of the Energy Generation Systems

As coal, gas and peat were not in the scope of the project either, fuel costs affect only the diesel generator. The consumption varies widely depending on the local conditions but it still depends almost linearly on the load [5]. As an example, with 50 % load a 1000 kW generator consumes 100 liters in one hour, which means 0.2 liters/kWh costing 0.2 €/kWh. With these prices diesel is only for supplying emergency power.

The price bids for the microgrid's energy are the sum of the fixed costs and the additional costs of generating energy. The additional costs are operation and maintenance costs, which realize sooner, if the generators run.

Table 5 presents the costs per year in € in Finland on March 2012. The expected lifetime of the generators is between 25 to 40 years and no interest rates are used in the calculations. The capacity factor is from [3], it estimates how much of the nominal capacity is actually utilized in one year. The costs of the photovoltaic system are an approximation based on [1], [3] and [4]. The costs of hydroelectric power are estimated from the costs of large plants that were recently built in the United States [3]. The major cost in hydro power plants comes from building the dam and in real small-scale systems either no dam is built or the building costs are relatively high when compared to large plants. Anyway, it is possible to implement a small-scale hydro generator system with about a tenth of the price of a photovoltaic system, if no dam is required.

Table 5. The investment costs per year in commercial systems

Energy source	Nominal Power [kW]	Investment [€]	O&M [€]	Capacity factor	Fixed costs [€/kWh]	Costs of generating energy [€/kWh]
Wind	1000	54400	8800	0.34	0.021	0.001
Photovoltaic	5,8	500[1]	90	0.25	0.046	0
Hydroelectric	400	9000	1000	0.66	0.004	0.0003
Diesel fuel	457	5600[2]	200	0.05	0.29	0.001[3]
Diesel fuel, low scale	100	750[5]	200	0.25	0.34	0.004[3]

[1]Price of 20 solar panels and equipment / 25 years

[2]The example price is for an Atlas-Copco 457 kW diesel generator set / 25 years

[3]without fuel costs

[5]The example price is for a Perkins 100 kW diesel generator set / 15 years [11]

8.3.2 The Costs of the Energy Storage Systems

The costs are calculated with a 15-year lifetime expectation. Operation and maintenance costs are not listed because they are rather low. Building a 200 kW inverter from small-scale devices would require additional assembling costs, which were not calculated. Most of the device vendors (e.g. ABB, Siemens) do not publish the prices of the more costly inverters and power supplies, therefore some of the given investment costs are only estimations.

Table 6. The costs of the energy storage systems

DEVICE TYPE	Brand / model	Capacity of one unit	Voltage	Investment [€ / year]
Battery bank	Rolls/Surrette	1600 Ah (76,8 kWh)	48 V	700[0]
Small-scale solar inverter	Danfoss TripleLinx TLX +15KW	15 kW	3X230V (AC)	197
Central solar inverter	CHNT Power CPS SC100KT	100 kW	AC 480 V	1450[1]
Central solar inverter	Power-One PVI-CENTRAL-250-US-480 250 kW Inverter	250 kW	AC 480 V	4280[1]
Central solar inverter	ABB PVS800	250 kW	AC: 240V	7000[2]
AC/DC Converter (Power Supply)	Magna-Power DC Power Supply	30 kW	DC: 50 V(max)	1200[3]
AC/DC Converter (Power Supply)	Magna-Power DC Power Supply	75 kW	DC: 50 V(max)	2200[3]

[0] from [12]

[1] from [9]

[2] Estimated, exact price should be asked from the vendor

[3] from [10]

8.3.2.1 Examples of Energy Storage Systems for a 100 kW Microgrid

If a microgrid can continuously generate power with lower costs than the market prices, selling all extra energy is a good choice. The energy storage systems are not necessary; they exist above all to secure the power supply.

Exact costs of energy storage depend on various complicated factors. The life expectancy of a battery system varies according to charging/discharging cycles. In addition, the energy loss in the storage process depends on quality and age of the battery systems. It is difficult to present the real costs of a stored kWh.

However, we illustrate the investment costs of storage systems with two example cases. This is to show the share of storage costs to the total costs of microgrid investments. The first case is a system, which can provide 76.8 kW at any instant. The second system can deliver 38.4 kW for 20 hours, when needed. The first one provides the typical power requirement of our example microgrid and the second give the basic requirement for emergency cases where consumption should be limited.

Clearly, the biggest costs come from the battery systems. The storage systems always increase the total costs of the microgrids still they advance the security of supplied energy. The costs per stored kWh are huge, but it is better to compare the yearly investment costs, which indicate the price of the better energy security.

Table 7. The 76.8 kW system (1536 kWh)

Device Type	Brand/model	Capacity of one unit	Investment [€/year]	Number of Units needed	Investment Costs per year
AC/DC Converter (Power Supply)	Magna-Power DC Power Supply	75 kW	2200	1	2200
Central solar inverter	CHNT Power CPS SC100KT	100 kW	1450	1	1450
Battery bank	Rolls/Surrette	1600 Ah (76,8 kWh)	700	20	14000
Total Costs		**172 [€/kWh]**			**17650 [€/year]**

Table 8. The 38.4 kW system (768 kWh)

Device Type	Brand/model	Capacity of one unit	Investment [€/year]	Number of Units needed	Investment Costs per year
AC/DC Converter (Power Supply)	Magna-Power DC Power Supply	30 kW	1200	1	1200
Small-scale solar inverter	Danfoss TripleLinx TLX +15KW	15 kW	197	2	393
Battery bank	Rolls/Surrette	1600 Ah (76,8 kWh)	700	10	7000
Total Costs		**167 [€/kWh]**			**8600 [€/year]**

The options of full investment costs of a microgrid are shown for comparison. Costs of security are close to the costs of the power generating systems. Using a diesel generator can be a cheaper option to ensure the microgrid's energy security.

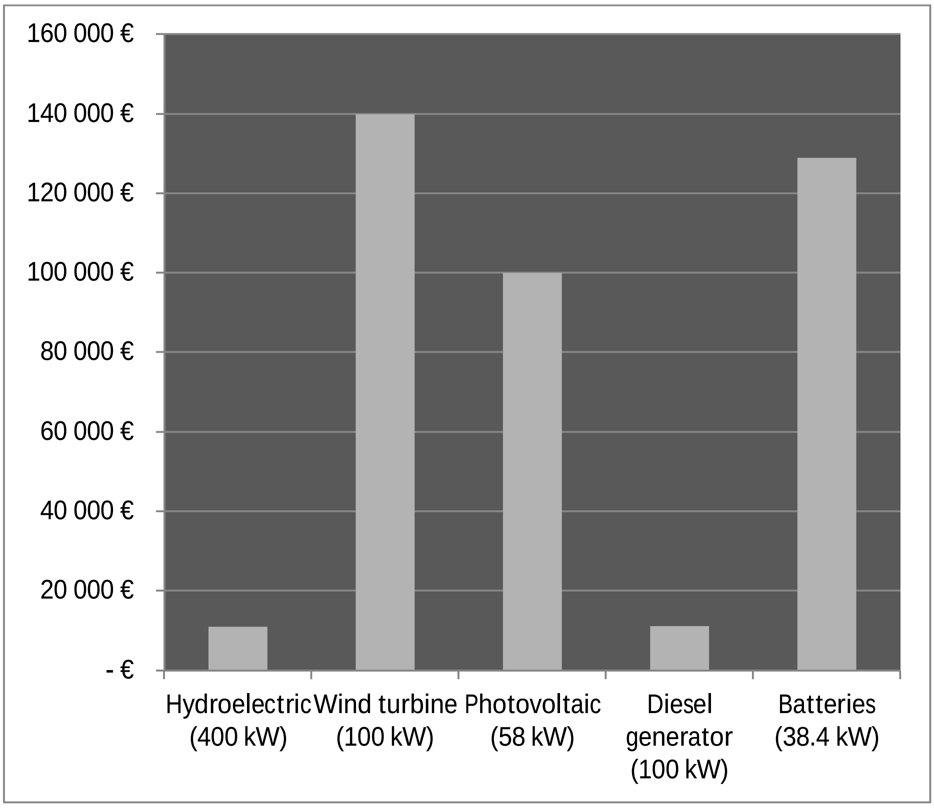

Figure 7. Optional investment costs of a microgrid capable of generating about 100 kW.

8.4 Generator Simulation Models

Figure 8 depicts the simulation model of the generator components in Simulink. The inputs are:

- Generator control: Control signal to switch generation on/off
- Power demand: When implemented, this signal can be used for demanding a distinct amount of power from the generators

Outputs are:

- Generated power: Total generated power of all generators
- Generator forecast: Predicted power generation
- DG cost: Total cost of locally generated power

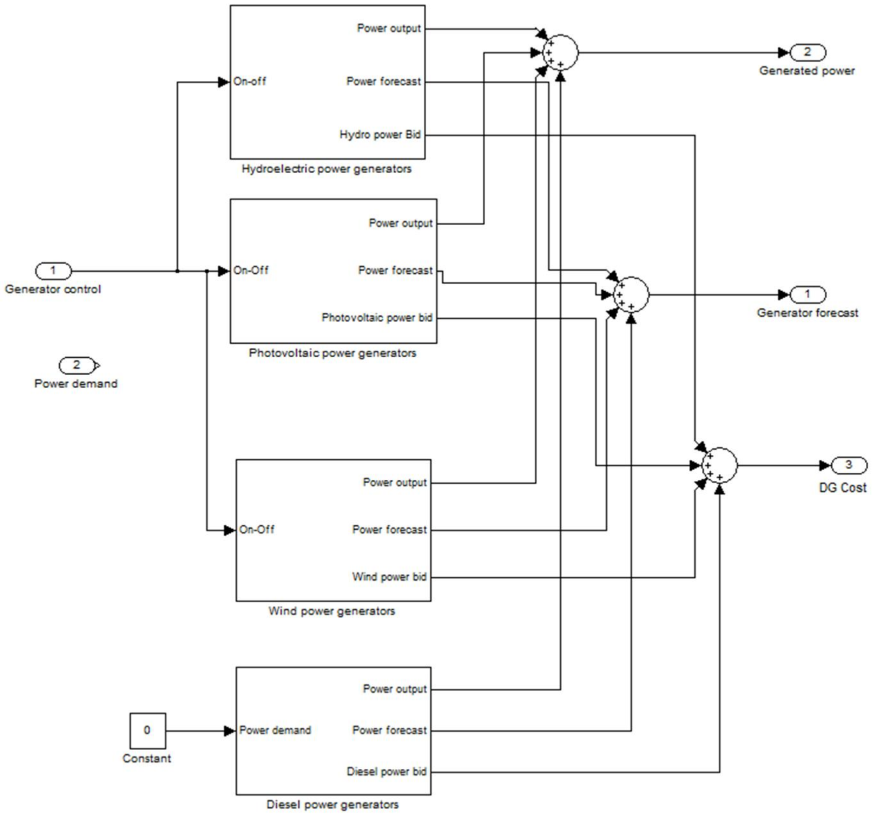

Figure 8. Generator Controller (GC) simulation model

Functions needed to simulate energy generation include more than the basic bid functions and the relevant models are described below.

8.4.1 Photovoltaic Power Generator

The Photovoltaic power generator calculates (with sub-function `solarcurrentplus.m`) a photovoltaic power bid as kilowatts for one hour from day and time information. It is assumed that:

1. Solar panels are always at the same place, which is in Finland (61^0 29′, 23^0 45′)

2. The ambient temperature and the solar irradiance are stepped variables, which change with one hour (irradiation) or one month's (temperature) steps. For example the ambient temperature in April is +3 C^0 constantly. Intensity of the received solar irradiation depends both on time of day and time of year. On any day in winter time at seven o'clock radiation is zero (0 W/m^2) but by the same time in mid-summer it is typically close to 400 W/m^2.
3. The solar panel's model is Suntech Pluto 290W (any panel can be used)
4. Power bid is always the maximum that the panel can offer to a matched load, no comparison with the actual load is done

Most of these assumptions can be rather easily changed, if needed. However, providing more options requires more parameters, much more input information and a more complex system.

The sub-function `Solarcurrentplus` calculates photovoltaic current from given irradiation and temperature. It takes also the Solar Panel's basic parameters (technical specifications) as input. Please note that some vendors present the temperature coefficients of the photovoltaic panels in their data sheets as "%/^{0}C", which must be mapped to A/^{0}C or V/^{o}C.

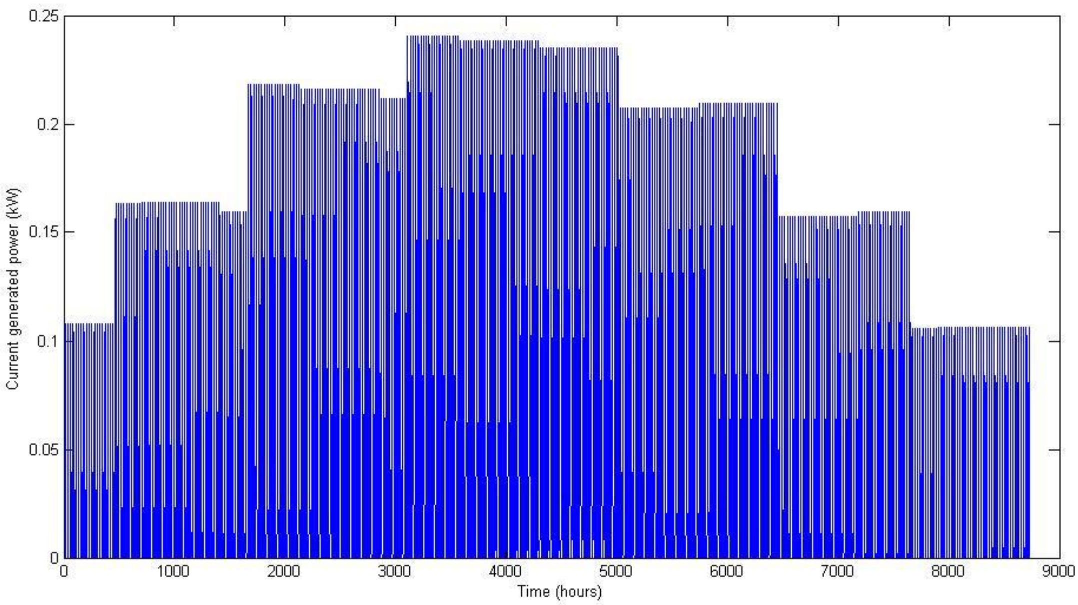

Figure 9. Hourly generated power of a single Photovoltaic power generator for a year with default parameters

Table 9. The input arguments of the photovoltaic power generator

ATTRIBUTES	Unit	Max	Min	Default value	Description
Number of photovoltaic elements	Piece	-	1	1	Number of photovoltaic elements

V_{OC}	V	100	0.1	45.1	Open circuit voltage of solar panel
I_{SC}	A	-	0.1	8.52	Short circuit current of solar panel
V_{MP}	V	V_{OC}	0.1	36.3	Voltage at Maximum Power Point of solar panel (STC)
I_{MP}	A	I_{SC}	0.1	7.99	Current at Maximum Power Point of solar panel (STC)
k_T	V/ºC	0	-	-0.1422	Temperature coefficient of solar panel's voltage (always negative)
m_T	A/ºC	-	0	+0.004	Temperature coefficient of solar panel's current (always positive)
Fixed cost	€/kWh	-	0	0.046	Fixed production costs (see section 4.2)
Production cost	€/kWh	-	0	0	Production costs (see section 4.2)

Table 10.The constants of the photovoltaic power generator

ATTRIBUTES	Unit	Max	Min	Default value	Description
G	W/m^2	800	0	800	Hourly intensity of solar irradiance in Finland
Temp	ºC	17	-8.5	25 ºC	Average monthly ambient temperature

Table 11.The output arguments of Photovoltaic power generator

ATTRIBUTES	Unit	Max	Min	Default value	Description
PowerBid	kW	-	0	0	Offered power for one hour as kilowatts, the bid can be zero e.g. at night time.
PowerForecast	kW	-	0	0	Forecast power for the next hour.
PowerCost	€	-	0	0	Cost of producing energy.

8.4.2 Hydroelectric Power Generator

Hydroelectric power generator calculates a hydroelectric power bid as kilowatts for one hour from day information. It is assumed that a hydroelectric power plant has a nominal capacity of 400 kW and that the water flow through the plant varies in a wide scale, as it varies at Tolpankoski, Oulainen, Finland.

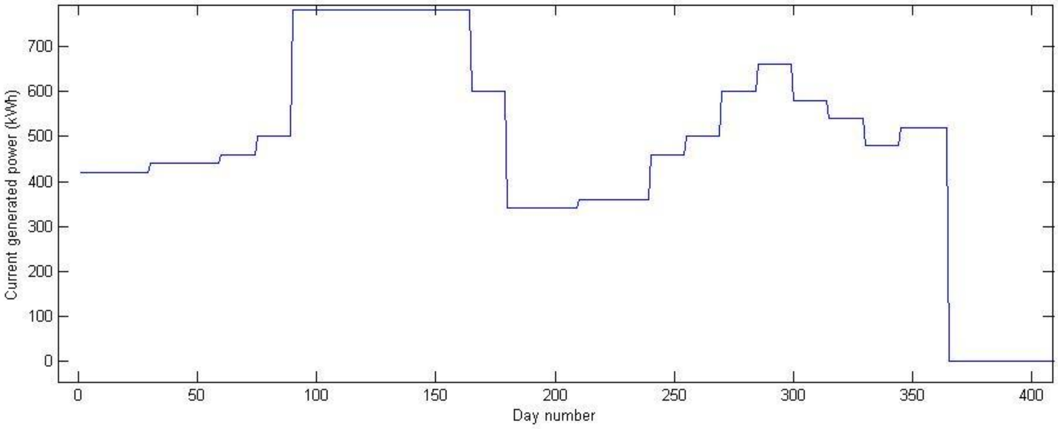

Figure 10. Generated power of a single hydroelectric power generator for a year with default parameters

Table 12. The input arguments of Hydroelectric power generator

ATTRIBUTES	Unit	Max	Min	Default value	Description
Maximum flow rate	m^3/s	-	1	39	Maximum flow rate caused by limitting the water level in the dam.
Nominal output power factor for a power plant	$kW/m^3/s$	-	1	20	The nominal output power factor for a power plant.
Number of power plants	Pieces	-	1	1	The number of plants
Fixed cost	€/kWh	-	0	0.004	Fixed production costs (see section 4.2)
Production cost	€/kWh	-	0	0.0003	Production costs (see section 4.2)

Table 13. The output arguments of the hydroelectric power generator

ATTRIBUTES	Unit	Max	Min	Default value	Description
Px	kW	-	0	0	Output power of the hydroelectric plant
Pforecast	kW	-	0	0	Forecasted output power of the hydroelectric plant
Pcost	€	-	0	0	Cost of producing energy.

8.4.3 Wind Power Generator

Wind power generator calculates (together with sub-function `Windpower`) a wind power bid as kilowatts for one hour from day information. The monthly average wind speeds and monthly average temperatures at Oulu region in Finland are assumed.

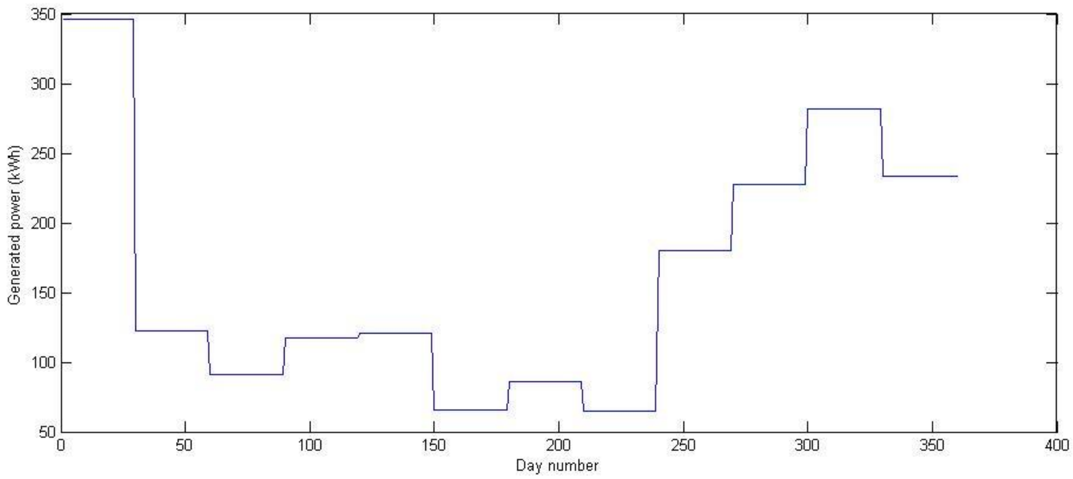

Figure 11. Generated power of a single Wind power generator for a year with default parameters

Table 14. The input arguments of Wind power generator

ATTRIBUTES	Unit	Max	Min	Default value	Description
Rotor diameter	m	-	1	60	Rotor diameter for a wind turbine. The default is for WinWinD's model WWD-1 wind turbine
Number of wind turbines	piece	-	1	1	Number of wind turbines
Cmax	-	-	0.01	1.146	Maximum power coefficient for a turbine to trim the output. The default is close to what WinWinDs model WWD-1 should provide (60 m diameter)
Cut_in	m/s	-	0.1	3.6	Cut-in wind speeds of the wind turbine (default for WWD-1)
Cut_out	m/s	-	0.1	20	Cut-out wind speeds of the wind turbine (default for WWD-1)
Rated speed	m/s	-	0.1	12.5	Above rated speed the output power stays stable (default for WWD-1)
Fixed cost	€/kWh	-	0	0.021	Fixed production costs (see section 4.2)
Production cost	€/kWh	-	0	0.001	Production costs (see section 4.2)

Table 15. The output arguments of Wind power generator

ATTRIBUTES	Unit	Max	Min	Default value	Description
Pwr	kW	-	0	0	Output power of the wind turbine
PwrForecast	kW	-	0	0	Forecasted output power of the wind turbine
PwrCost	€	-	0	0	Cost of currently produced energy

Sub-function `Windpower` calculates the output power of a wind turbine from the rotor's size, ambient temperature, speed of wind, maximum power coefficient, cut-in speed, cut-out speed and rated speed.

8.4.4 Diesel Power Generator

Diesel power generator returns the available diesel power and the fuel consumption as litres/hour. A diesel engine can deliver its nominal power under any weather conditions, if only fuel is available.

Table 16. The input parameters of Diesel power generator

ATTRIBUTES	Unit	Max	Min	Default value	Description
Power requirement	kW	-	0	0	Requested electrical power
Maximum generator capacity	kW	-	1	1026	Maximum generator capacity (default is Wärtsilä 20 diesel engine)
Fuel consumption	l/h	-	1	240	Fuel consumption (default is Wärtsilä 20 diesel engine)
Fixed cost	€/kWh	-	0	0.029	Fixed production costs (see section 4.2)
Production cost	€/kWh	-	0	0.001	Production costs (see section 4.2)
Fuel cost	€/l	-	0	1.01	Cost of diesel fuel

Table 17. The output parameters of Diesel power generator

ATTRIBUTES	Unit	Max	Min	Default value	Description
Pd	kW	1026	102.6	0	Output power
PdForecast	kW	1026	102.6	0	Forecasted output power
PdCost	€	-	0	0	Cost of producing energy

9 Load Controller

The load controller is responsible for handling the load control commands from the MGCC. It is assumed that there is always enough energy provided to the loads so that the energy is distributed on demand.

Table 18. The input arguments of Load Controller

ATTRIBUTES	Unit	Max	Min	Default value	Description
Power	kWh	-	-	-	Power needed by the all loads in total
Load control	-	-	-	-	Load control command from MGCC

Table 19. The output arguments of Load Controller

ATTRIBUTES	Unit	Max	Min	Default value	Description
Load forecast	kWh	-	-	-	Total power demand forecast for next 12 hours in microgrid
Load current	kWh	-	-	-	Current power demand in microgrid

9.1 Load Simulation Models

The loads consist of family houses with electrical heating system. It was decided that the microgrid consists of one hundred (100) single-family houses with similar loads. Figure 12 depicts one of these houses. The inputs are:

- Simulation time: The load demand of the house depends on what time it is
- Control command: check table 18
- Temp_current and temp_12h_avg: Power demand of the heating system depends on the outside temperature

Outputs are defined in table 21.

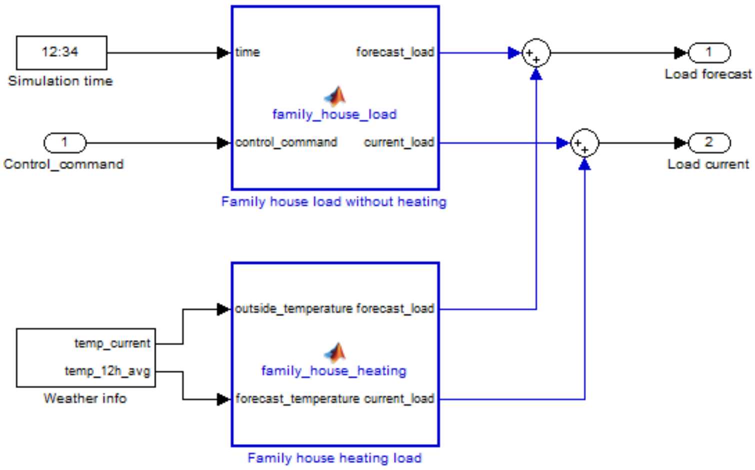

Figure 12. Load block of a single-family house

9.1.1 Family House Load

The family house loads consist of single-family house with electrical heating system. The Family house load is based on Riku Pasonen's diploma thesis [6]. The load is divided into heating load and other loads.

Family house heating load assuming electrical heating is based on data from Savon Voima website [13] containing typical family house loads. The heating is turned off if current outside temperature is above +10 ºC. Otherwise the required heating power is directly proportional to the outside temperature based on the parameters `Slope for heating` and `Constant for heating.` The outside temperature is based on weather in Helsinki, Finland.

Other loads in the family house consist of two types of fixed load, high and low spread, and controllable loads. The load is based on data from [7].

The forecast loads are calculated similarly using 12 hour forecast weather data and forecasted energy consumption.

The load produced in every simulation run is randomized by maintaining about 20kWh yearly load for each house with the default parameters as the depicted in typical energy profile below.

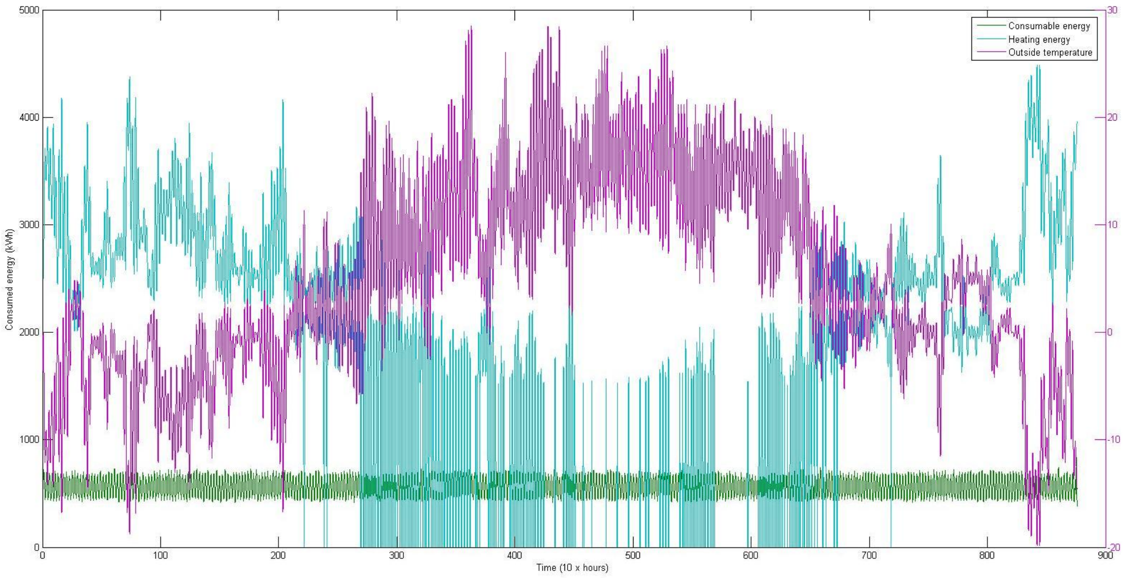

Figure 13. Yearly 12 hour averaged energy profile of a single family house with default parameters without load control

Table 20. Parameters of Family house load

ATTRIBUTES	Unit	Max	Min	Default value	Description
Share of the controllable load	decimal	1	0	0.5	Defines how much of the total load is controllable (not including heating).
Share of the high spread fixed load	decimal	1	0	0.33	Defines how much of the fixed load is high spread. Rest of the fixed load is low spread (not includeing heating).
ID of the house	integer	-	1	1	Unique ID of the house
Slope for heating	W/C	-	0	100	Defines the correlation between outside temperature and required heating power
Constant for heating	W	-	0	1500	Defines the minimun amount of heating power

Table 21. The input arguments of a family house load

ATTRIBUTES	Unit	Max	Min	Default value	Description
Control command	hour	12	0	0	Command from MGCC which defines a delay to use controllable load. Next command can be applied after 2 x delay issued. 0 denotes not used.

Table 22. The output arguments of a family house load

ATTRIBUTES	Unit	Max	Min	Default value	Description
Load forecast	kWh	-	-	-	Single house power demand forecast for next 12 hours
Load current	kWh	-	-	-	Current power demand for a single house

10 Results

The results of the microgrid simulations with Ideal Citizen policy with 100 family house loads are presented in figure 13. The operation of this particular policy can be judged based on overall operational costs in the microgrid. The reference cost indicates the cost if the microgrid has no energy production, no load control and no energy storages. Three different scenarios have been simulated:

1) Without load control nor MG energy storages

2) Without load control but with MG energy storages

3) With load control and MG energy storages

Energy costs do not include transfer prices, feed-in-tariffs or any other kind of governmental support for the microgrid.

The overall profitability of the microgrid depends also on the investment costs. The following table summarizes the overall profitability.

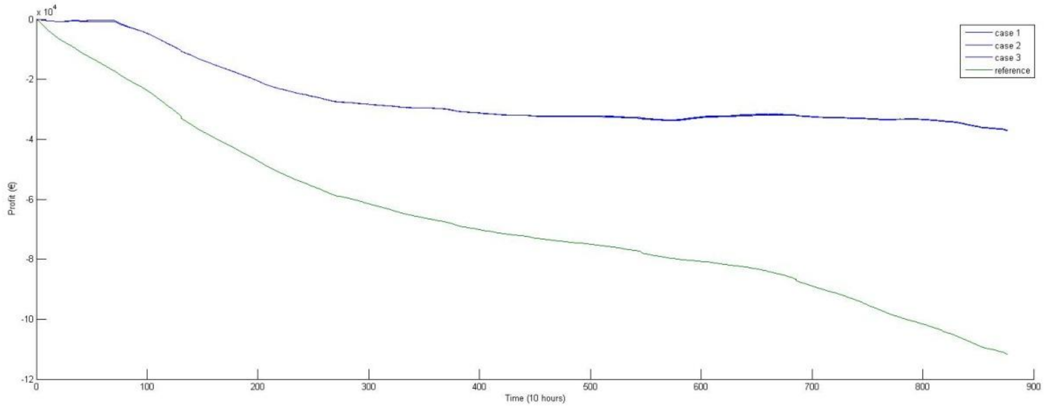

Figure 14. Operational costs of the microgrid (Policy B)

Table 23.Profitability

Case	Equipment	Investment costs (€/ y)	MG gain (€/y)	Total MG profit (€/y)
No load control No MG energy storages	100 pcs. Suntech Pluto 290W 1 pc. WWD-1 1000kW 1 pc. Wärtsilä 20 (1026kW) Total	2 000 54 400 10 000 66 400	74 362	7 962
No load control With MG energy storages	100 pcs. Suntech Pluto 290W 1 pc. WWD-1 1000kW 1 pc. Wärtsilä 20 1026kW 20 pcs. Rolls/Surrette 76.8 kW Total	2 000 54 400 10 000 17 650 84 050	74 500	-9 550
With load control With MG energy storages	100 pcs. Suntech Pluto 290W 1 pc. WWD-1 1000kW 1 pc. Wärtsilä 20 1026kW 20 pcs. Rolls/Surrette 76.8 kW Total	2 000 54 400 10 000 17 650 84 050	74 551	-9 499

The diesel generator is practically never used in the simulation. Therefore, it would be better to utilize a Perkins 100 kW diesel generator instead of a 1000 kW resulting in a 9000 €/y lower investment costs. Similarly, the usage of a smaller wind turbine such as 100kW would result 50 000 €/v lower investment costs that could affect significantly the total profitability of the microgrid. Still the 100 kW Wind Turbine (nominal) provides only tens of kilowatts of actual power. The investment costs do not include the general cost for building a microgrid e.g. energy transfer infrastructure.

The simulations show that the rough load control scheme implemented does not affect the operation of the microgrid much. The situation might improve if a larger amount of load could be controlled and the usage of the controlled load could be spread to a longer timespan resulting in flat overall load curves. Since in the model the heating of the family house loads is not controllable, the variance of the overall load is too high to result in significant savings with load control.

Similarly, the usage of MG energy storages is insignificant to the operational costs. To achieve gains with the use of the storages the market prices should be predicted accurately in the near future or the difference between buying and selling prices from the DSO should be higher.

In general the operation of the microgrid in the simulated year is highly profitable (with energy transfer prices or general microgrid investment costs) in spite of lost profit in the spring time when the weather conditions lead to low RES power generation but energy consumption remains high. If a microgrid can continuously generate power with lower costs than the market prices, selling all extra energy is a good choice. The energy storage systems are not necessary; they exist above all to secure the power supply.

11 Future Work

At the moment the simulation model implements the reference case and the Policy B (Ideal Citizen) case. Next we will implement Policies A (Good Citizen) and C (Green Policy). We need to do more simulations with varied loads and scenarios. This will give us much more data to analyse.

Load and generation components calculate load and power forecasts. This information is not used by the simulation model. These forecasts could be a huge benefit in preparing for higher power demand or for lower local generation.

12 References

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