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A study for an optimization of a hybrid renewable energy system as a part of decentralized power supply

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Abstract

The objective of this paper is to describe the optimization of a hybrid renewable energy system. The system is intended to supply a residential neighborhood with thermal and electrical power. A software based model has been developed to serve as an experimental tool for calculations and comparison. The aim of the research is to find an optimal size per each element of the system due to the demand to keep the system as independent from the public grid as it is possible. The proposed system model consists of a combined heat and power plant, thermal boiler and a photovoltaic array with an additional lithium-ion battery for electrical energy storage. A methodology based on optimal power production for maximal covering of consumer`s demands is applied in a combination with approximate prizes per natural gas, prizes per purchased and sold back electrical energy from and to the utility grid. Results formed as graphs and comparable cases are expected as outcomes, based on the most optimal calculations for lowest net present cost per purchases from the utility grid.

Keywords: Thermal boiler, combined heat and power plant, photovoltaic array, lithium-ion battery system

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1. Introduction

During the past years an intensive research and a careful development of utilization strategies for renewable energy sources were introduced. In the upcoming years most estimates of the potential growing consumption predicts that the global energy demand will become double by the year 2050 [1]. This growing potential must be met from the nowadays power grids with all their available capacity. On another hand the demand from more electrical power and respectively heat power will lead to inevitable request for relevant power lines which have to be able to face the growing consumption. This will lead to increased costs for maintenance and repair about the existing power lines and also a huge financial disadvantage because of the necessity from new traditional power distribution lines and facilities.

The most important tasks for the new generation of power grids are the minimization of consumption from consumer`s side with an implementation of more effective technologies and loss reduction from the grid`s side. Next generation grids must meet the greenhouse gas emissions requirements (20-20-20 targets of the European Commission) by switching to renewable energy sources [2].

Furthermore the concept and ideas for a step from the traditional centralized power generation towards a regional decentralized power generation will become more popular, because of the potential for minimal electrical losses due to power distribution from a distant conventional power plant. In [3] a software model of a decentralized hybrid power generation system was introduced and matched with a real hybrid system and finally verified in [4]. It represents the idea of merging the traditional heating method for households with renewable technologies and cogeneration of electrical power during heating. A structure with functional blocks is used for the actual model [5] and it is based on an existing hybrid distributed generation system.

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The referred system ([3], [4]) supplies thermal and electrical power to a residential area which comprises 180 town houses. It consists of a combined heat and power plant (CHP) with a nominal electrical power of *50 kWel* and a thermal power of *81 kWth*. A peak load boiler with a rated power of *895 kWth* is used to cover the complete energy demand of a residential neighborhood during high consumption via two heat storage tanks. In order to reduce the power flow from the public grid a photovoltaic system (PV) with a peak power of *63 kWp* has been installed. A lithium-ion battery with a nominal power of *50 kW* and a capacity of *135 kWh* is integrated to compensate the fluctuating power generation of the PV system. The architecture of the plant is implemented in the Homer simulation environment as shown in Fig. 1 which will be explained in the following paragraphs.

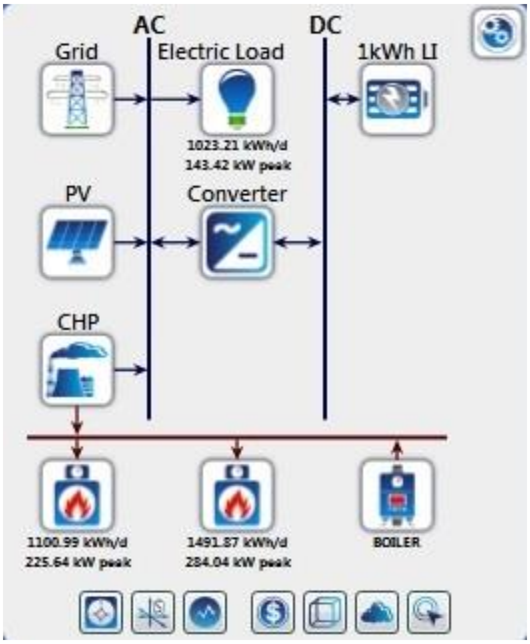


Fig. 1. Architecture of the hybrid renewable energy system implanted in homer.

Thermal power is distributed via an underground district heating network which connects a combined heat and power plant, a peak load boiler and the residential consumers. For a higher flexibility of the heat distribution network all consumers are separated in two groups. The PV system is modelled according a plan for approximate calculations of electrical consumption [6]. All electrical sources and loads are connected to a low-voltage AC power distribution network with a rated voltage of 400V [7].

2. Impact of the Paper and Main Conditions of Modelling

The goal of this paper is to show an optimisation of the system considering different parameters like prices of the facilities, fuel in use and expenses per heating and electricity. The point is to keep the system independent from the public grid as much as possible. All models have been developed with the help of Homer Pro Microgrid Analysis Tool v.3.7.5 [8]-[9].

2.1. Construction of electrical and thermal loads

Primary load is electrical load that the system must meet immediately in order to avoid unbalanced load conditions. In each time step of the simulation solver, HOMER dispatches the power producing components of the system to serve the total primary load. Load profiles are generated from the referred plant. In this manner average hourly values are used when the hour-by-hour monthly profiles are implemented.

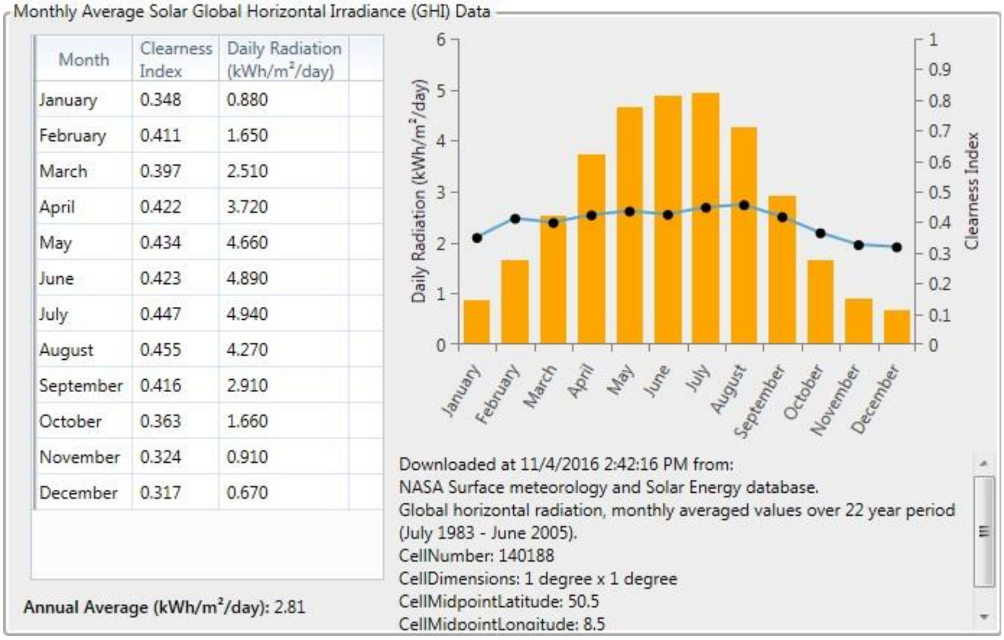
2.2. Photovoltaic array

The rated power of the photovoltaic array is based on the referred system. The Homer Pro input window allows to enter cost information, performance characteristics and orientation of the array`s panels. It provides also a choice regarding the size values for optimisation. As main algorithm the following equation is adapted:

$$P_{PV} = Y_{PV}.f_{PV}.\left(\frac{G_T}{G_{T,STC}}\right).[1+\alpha_P.(T_c - T_{c,STC})] \tag{1}$$

where:
Y_{PV} – is the rated capacity pf the photovoltaic (PV) array [kW];
f_{PV} – PV derating factor [%];
G_T –is the solar radiation incident on the PV array in the current time step [kW/m^2];
$G_{T,\,STC}$ –is the incident radiation at standard test conditions [1 kW/m^2];
α_P – is the temperature coefficient of power [%/°C];
T_c –is the PV cell temperature in the current time step [°C];
$T_{c,\,STC}$ –is the PV cell temperature under standard test conditions [25°C]

The photovoltaic array model is linked to files which include the required information related to ambient conditions, like temperature and solar irradiation. An example of such a file, loaded in the model for the solar irradiation in the area of town Kelsterbach, Germany is represented on Fig. 2.



Monthly Average Solar Global Horizontal Irradiance (GHI) Data

Month	Clearness Index	Daily Radiation (kWh/m^2/day)
January	0.348	0.880
February	0.411	1.650
March	0.397	2.510
April	0.422	3.720
May	0.434	4.660
June	0.423	4.890
July	0.447	4.940
August	0.455	4.270
September	0.416	2.910
October	0.363	1.660
November	0.324	0.910
December	0.317	0.670

Annual Average (kWh/m^2/day): 2.81

Downloaded at 11/4/2016 2:42:16 PM from:
NASA Surface meteorology and Solar Energy database.
Global horizontal radiation, monthly averaged values over 22 year period (July 1983 - June 2005).
CellNumber: 140188
CellDimensions: 1 degree x 1 degree
CellMidpointLatitude: 50.5
CellMidpointLongitude: 8.5

Fig. 2. A file with input data for PV array with monthly values for solar irradiation.

The mentioned input files are downloaded from an internet database for the project location. The software automatically reads the data from this file. It also can load and read a file with a temperature database for the same location as an additional input quantity, required for calculations of the temperature influence on generated outgoing power from the photovoltaic array.

2.3. Utility grid

In Homer Pro the utility grid is represented with many quantities like purchase and sale capacity in kW per each month or annualized values, rate definitions for the prices per purchased and sold back energy in

USD/kWh, demand rates with programmable costs, reliability schedule and maintenance costs, emissions, extension expenses. Most important for the optimisation in this case are sale capacities which are the maximal power that can be sold back to the grid in kW as well as the purchase capacity [10]. It can be assumed that the maximal purchased grid power can correspond to grid feeding capacity at the node of connection. Some constraints are applied in case to prohibit any possibility of charge or discharge the battery system from the utility grid. The reason for this is related with the idea to keep the battery system as a buffer between public grid and the hybrid system.

2.4. Battery system

The software offers several kinds of storage devices and some different battery types. At this case an advanced storage module with Li-Ion cells is implemented and it uses the Kinetic Battery Model (Manwell and McGowan, 1993) to determine the amount of energy that can be absorbed by or withdrawn from the storage bank each time step. Using differential equations, one can show that the maximum amount of power that the storage can discharge over a specific length of time Δt is given by the following equation:

$$P_{batt,cmax,kbm} = \frac{k.Q_1.e^{-k\Delta t}+Qkc(1-e^{-k\Delta t})}{1-e^{-k\Delta t}+c(k\Delta-1+e^{-k\Delta t})} \tag{2}$$

where:
Q_1 - is the available energy [kWh] in the storage at the beginning of the time step;
Q - is the total amount of energy [kWh] in the storage at the beginning of the time step;
c - is the storage capacity ratio [unitless];
k - is the storage rate constant [h^{-1}];
Δt - is the length of the time step [h].

Similarly, the maximum amount of power that the storage can absorb over a specific length of time is given by the following equation:

$$P_{batt,cmax,mcr} = \frac{(1-e^{-\alpha_c \Delta t})(Q_{MAX}-Q)}{\Delta t} \tag{3}$$

where:
a_c is the storage's maximum charge rate [A/Ah];
Q_{max} is the total capacity of the storage bank [kWh].

A size of 1 kWh is determined as a minimal value for calculations, a maximal limit of 150 kWh is set as an upper limit per most of the simulations, excluding the cases where the software calculates scenarios without a battery system. A temperature influence from outside that the software offers is not included, because the battery system is placed in an air-conditioned operating room.

2.5. AC-DC converter

The Converter window allows defining the costs of the converter as well as any specific inverter and rectifier parameters. In order to provide more flexible simulation results the output power of the converter can be variable. It also uses an efficiency curve for both directions of power transfer. In this case the converter is connected with the battery system in order to ensure a possibility for loses implementation as in the real system. The size limit per this device is set from 0 kW to 100 kW.

2.6. Combined heat and power plant

The combined heat and power plant (CHP) is represented from an element that represents a gas turbine. It produces electrical and thermal power as outputs. This block element offers many options for optimisation, but the most important for this study is the output sizing and cost determination. It can also be scheduled to run constantly or in demands related mode. By default, HOMER decides each time step whether or not to operate the generator based on the electrical demand and the economics of the generator versus other power sources. For more comprehensive results the size of CHP unit is determined to have variable values in the range from 0 kW to 150 kW.

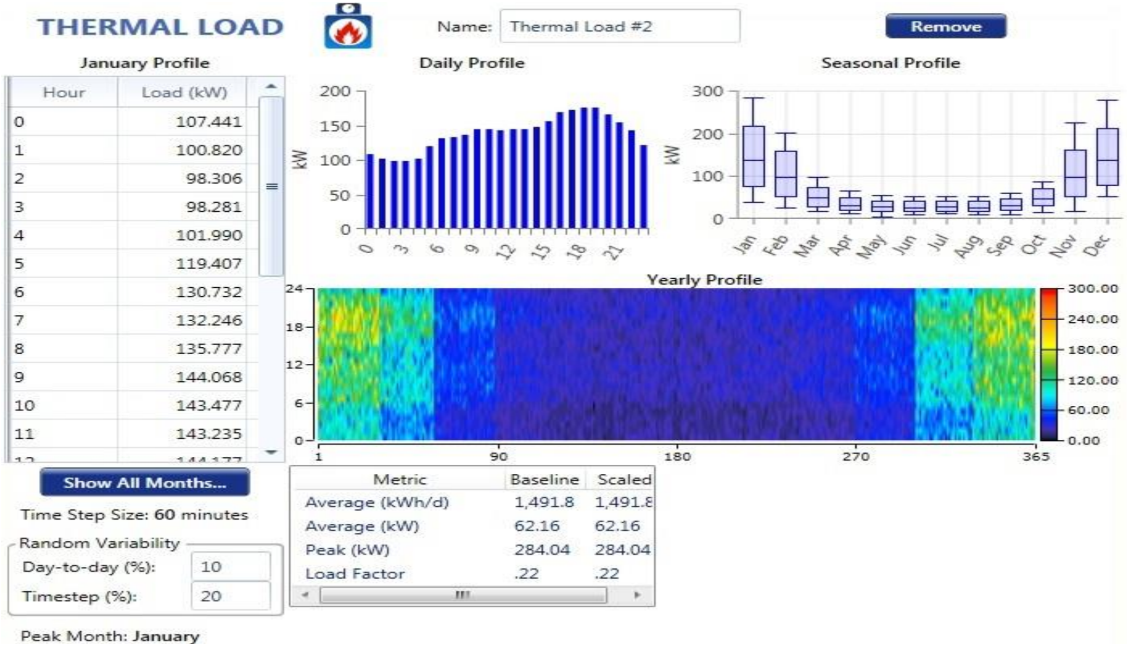
2.7. Peak load boiler

Most of the heating systems require the implementation of a boiler. HOMER does not account for capacity shortage of the thermal load, and so any portion not met from the CHP will be supplied by the boiler. This is also why the capacity of the boiler is unlimited. Most of the optimization parameters are related with the environmental effects caused from the outgoing exhaust gases.

3. System Circuit Definition and Initial Conditions of the Optimisation

3.1. Thermal circuit

The heat circuit starts with the heat consumers. According to the data processing from the real system a profile for each of both separated consumers is prepared, respectively the first thermal consumer has average thermal power of 45.87 kW and peak load equal to 225.64 kW. The second one is with average thermal power of 62.16 kW and peak load equal to 284.08 kW. According the system diagram they are linked with a natural gas fed peak load boiler. Diagrams per annual thermal load distribution divided by hours is represented on Fig. 3.



Name: Thermal Load #2

January Profile

Hour	Load (kW)
0	107.441
1	100.820
2	98.306
3	98.281
4	101.990
5	119.407
6	130.732
7	132.246
8	135.777
9	144.068
10	143.477
11	143.235

Time Step Size: 60 minutes

Random Variability

Day-to-day (%): 10

Timestep (%): 20

Metric	Baseline	Scaled
Average (kWh/d)	1,491.8	1,491.8
Average (kW)	62.16	62.16
Peak (kW)	284.04	284.04
Load Factor	.22	.22

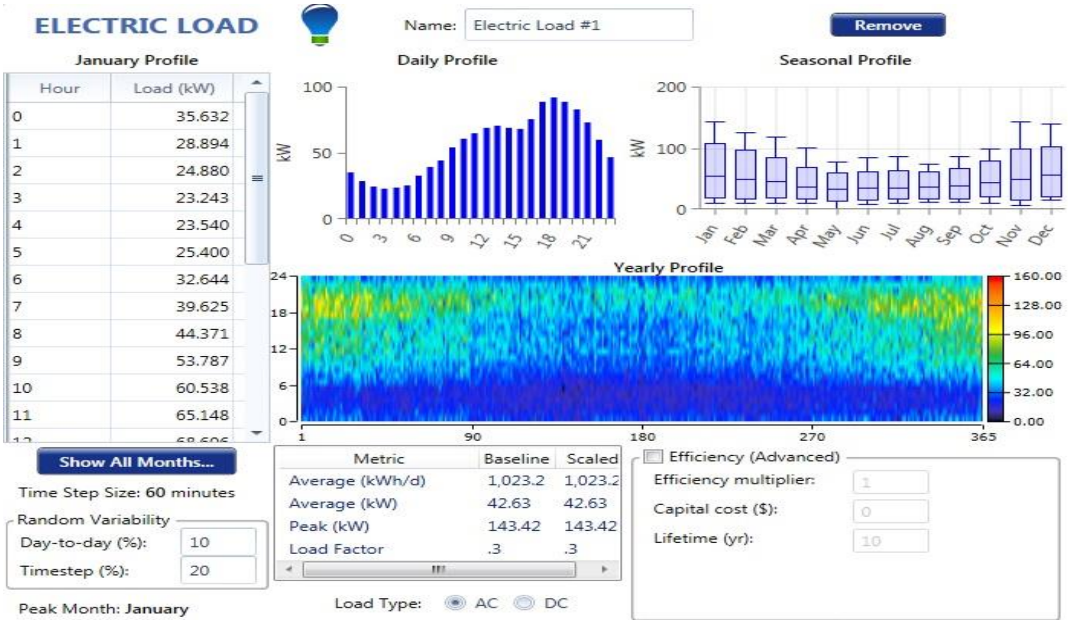
Peak Month: January

Fig. 3. Annual thermal load distribution

The efficiency of the peak load boiler is set at 85% and the price per cubic meter of natural gas is set with five different values in order to achieve different case scenarios during the optimisation process. The combined heat and power plant is also connected to the thermal circuit. The values of the rated power are set as initial possible cases (from 25 kW up to 150kW) regarding both outgoing electrical and thermal power. The preferred schedule for the CHP unit is chosen as continuous from weekend and continuous way of performance.

3.2. Electrical circuit

The electrical circuit starts with a formation of the electrical load profile. A residential type of consumer has been set with an average load equal to 42.63 kW and a peak load with a value of 143.42 kW. It is connected to the AC system bus-bar. A diagram with the loads is placed on Fig. 4.



Name: Electric Load #1

January Profile

Hour	Load (kW)
0	35.632
1	28.894
2	24.880
3	23.243
4	23.540
5	25.400
6	32.644
7	39.625
8	44.371
9	53.787
10	60.538
11	65.148

Time Step Size: 60 minutes

Random Variability

Day-to-day (%): 10

Timestep (%): 20

Peak Month: January

Metric	Baseline	Scaled
Average (kWh/d)	1,023.2	1,023.2
Average (kW)	42.63	42.63
Peak (kW)	143.42	143.42
Load Factor	.3	.3

Load Type: ● AC ○ DC

☐ Efficiency (Advanced)

Efficiency multiplier: 1

Capital cost ($): 0

Lifetime (yr): 10

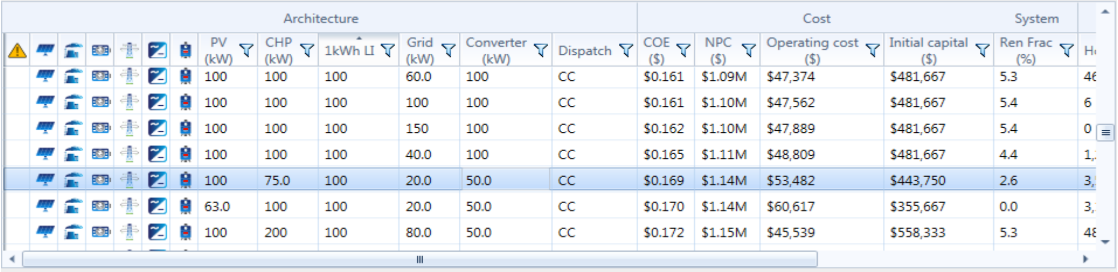
Fig. 4. Annual electrical load distribution

The link with the utility grid is also formed at the AC bus-bars and it has a sale capacity equal to 150 kW as an upper limit for the generated surplus power during the daily time with lower electrical consumption and higher power production. Another important quantity of the utility grid is the purchase capacity. It is adjusted with values from 20 kW up to 100 kW. Also several different prices per electricity are picked up and set as values for the analysis. The battery system is connected to the AC bus-bar via a converter with an efficiency of 80 % and a lifetime of 15 years. Regarding the battery system itself it is with several values for capacity close to the capacity of the real battery system. As initial state of charge (SOC) for the battery system is assumed that it is fully charged and it has an end value for SOC equal to 20% of its capacity. The battery of use in the model has a nominal voltage equal to 6V, a nominal capacity equal to 1 kWh with an option to be multiplied with the previously set values for capacity.

4. Simulation Results

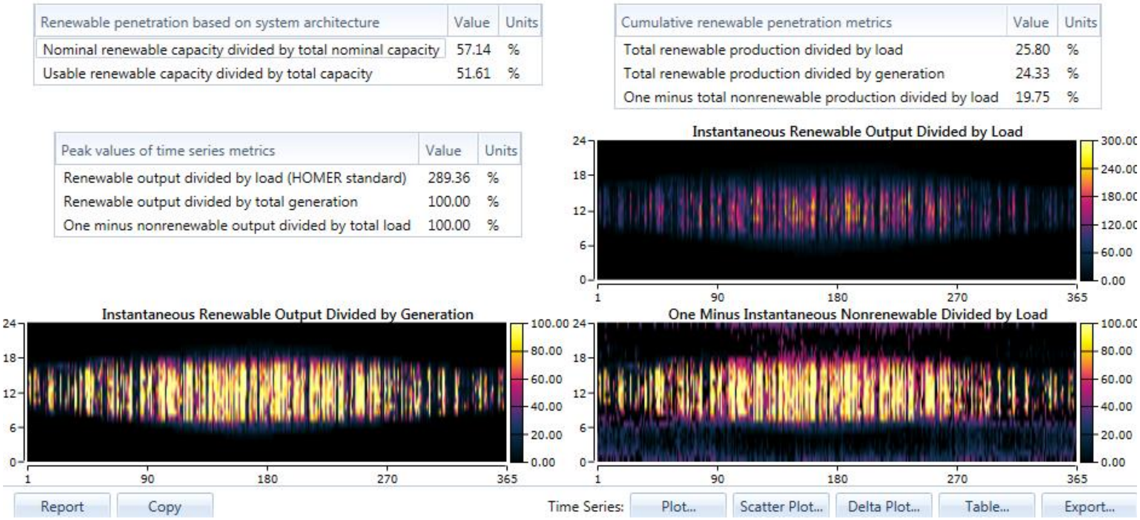
After all the adjustments briefly reviewed in the previous section are ready, a simulation is performed. The results are sorted regarding the chosen optimization criteria. All outcomes can be aligned according one or more reference quantities as it is shown on Table 1.

Table 1. A part of the possible cases for system structure are placed.



Architecture						Cost				System	
PV (kW)	CHP (kW)	1kWh LI	Grid (kW)	Converter (kW)	Dispatch	COE ($)	NPC ($)	Operating cost ($)	Initial capital ($)	Ren Frac (%)	H
100	100	100	60.0	100	CC	$0.161	$1.09M	$47,374	$481,667	5.3	46
100	100	100	100	100	CC	$0.161	$1.10M	$47,562	$481,667	5.4	6
100	100	100	150	100	CC	$0.162	$1.10M	$47,889	$481,667	5.4	0
100	100	100	40.0	100	CC	$0.165	$1.11M	$48,809	$481,667	4.4	1,
100	75.0	100	20.0	50.0	CC	$0.169	$1.14M	$53,482	$443,750	2.6	3,
63.0	100	100	20.0	50.0	CC	$0.170	$1.14M	$60,617	$355,667	0.0	3,
100	200	100	80.0	50.0	CC	$0.172	$1.15M	$45,539	$558,333	5.3	48

At this case the rated power of the photovoltaic array is accepted as a constant for each specific calculated case scenario, then it is changed in order to repeat the calculations. All other quantities are variable and also the cases without one or more elements can be observed. By double clicking on one of all the simulated case scenarios a pop up window with several subcategories of graphs will appear. There it can be found information regarding most of the elements and their annual performance. The penetration level of the energy generated by the photovoltaic array can be also estimated and expressed by the software as one of its base features as it is shown on Fig. 5.

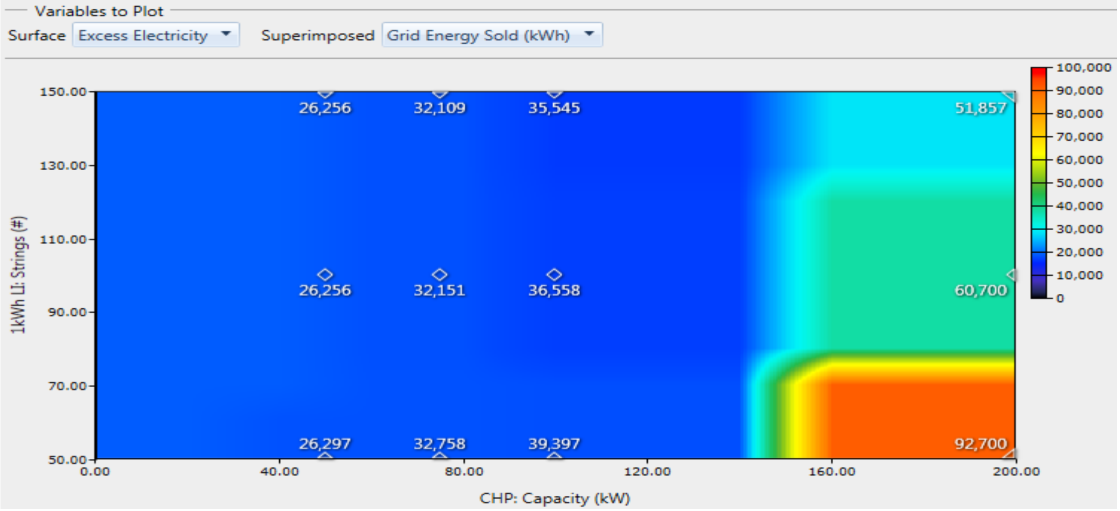


Renewable penetration based on system architecture	Value	Units
Nominal renewable capacity divided by total nominal capacity	57.14	%
Usable renewable capacity divided by total capacity	51.61	%

Cumulative renewable penetration metrics	Value	Units
Total renewable production divided by load	25.80	%
Total renewable production divided by generation	24.33	%
One minus total nonrenewable production divided by load	19.75	%

Peak values of time series metrics	Value	Units
Renewable output divided by load (HOMER standard)	289.36	%
Renewable output divided by total generation	100.00	%
One minus nonrenewable output divided by total load	100.00	%

Fig. 5. A representation of the calculated penetration levels for the PV power production and its impact of the system load, based on annual calculation for a different sizes of PV array.



Variables to Plot

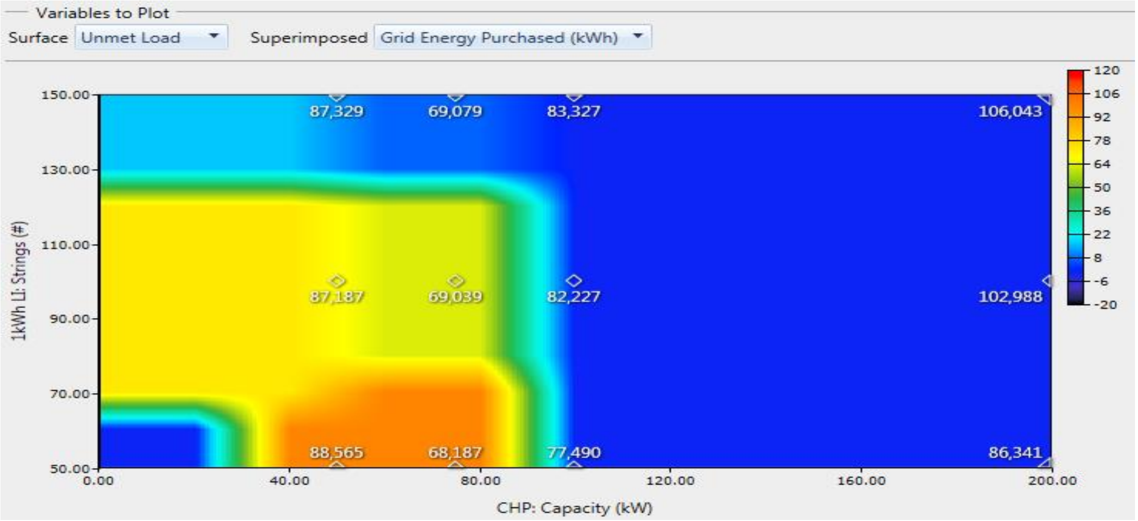
Surface: Excess Electricity

Superimposed: Grid Energy Sold (kWh)

Fig. 6. A graphical diagram for the generated surplus power in the system with different sizes for CHP and battery.

With these kinds of results an estimation of the load directly covered from the PV array can be performed. Furthermore the load share covered from PV power can be increased, but it will lead to increment of the costs for a PV system with higher size. On another hand a calculation regarding the size of the battery system and CHP can also be performed regarding the size of the PV array with a monitoring of surplus power production, after the demands of the system are covered by the generated power. This case scenario is visualized on Fig. 6.

With different values regarding the size of each element a balance in the system's performance can be reached, but the correct sizing of the system depends of the cost preferences. Another assessment criteria is the system's ability to meet all or most of its own demands. The outcomes regarding this criteria are visualized on Fig. 7.



Variables to Plot
Surface Unmet Load
Superimposed Grid Energy Purchased (kWh)

Fig. 7. A graphical diagram for the unmet load demands and the purchased power from the public grid.

In this research many possibilities of optimal system sizing can be reached, but regarding covering the demands of consumers and generated surplus power, the outcomes so far show that if a balanced sizing of the elements is applied, then most of the electrical demands can be met and the generated surplus power can be minimized.

5. Conclusions

After an outcome analysis is performed, it can be considered which size can be used for the actual hybrid renewable energy system in order to improve the present performance or for future projects regarding the actual demands. The sizing of each facility depends on the actual decision. Will the system be optimized regarding best cover of consumer's demands or regarding the costs of each subsystem. As a further development a research based on price analysis will be performed in order to estimate the efficiency of size optimization.

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