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Step By Step Numerical Approach to a Self-Sufficient Micro Energy System Design

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Abstract
This paper presents a numerical approach to self-sufficient energy-system design. The main focus is to describe the methodology of designing an approach in several steps to find an optimally structured micro-energy system in accordance with the introduced decision parameters. A specific system model is presented that consists of an energy consumer, renewable and non-renewable energy-production facilities, energy-storage capacities and a control unit. Different operating conditions were identified for the system and various system configurations were simulated. Based on the input data and the decision parameters an optimal system was chosen that is able to provide a stable and optimal energy supply. The optimal configuration was found using the WSM method. The result is a specific structure of the energy system that meets all the requirements and boundary conditions of the presented numerical approach. Finally, the operation of the system is presented via timeline charts.
Keywords: numerical model, energy system, optimization, operating regimes, RES, costs, energy demand, Matlab

Nomenclature

Symbols

a	-	annuity factor
c	€/kW	specific cost
C	€	cost
CPR	-	electricity consumption production ratio
E	kW	energy
f	-	parameter
h	m	height
H_f	kWh/kg	calorific value of fuel
I	W/m^2	solar radiation
$LCOE$	€	levelized cost of electricity
m	kg	mass
$m_{dp,i}$	-	value of the decision parameter
n	year	investment period
p	bar	pressure
P	kW	power
RF	-	renewability factor
r	-	interest rate
T_L	-	weather factor
β_S	°	surface slope
η	-	efficiency
θ	°	illumination angle

Subscripts

0	initial, normal value
a	annual fixed cost
cons	consumption
dp	decision parameter
el	electricity
f	fuel
HE	hydroelectric power plant
i	initial (cost)
in	incoming
ICE	internal combustion engine
max	maximum
min	minimum
om	operating and maintenance cost
out	outgoing
p	peak
prod	produced
renew	renewable
re-use	re-use
tot	total
use	used
WSM	weight-sum method

I. Introduction

Due to growing global energy demands, the world's reserves of fossil fuels are steadily decreasing, while their price is increasing. These facts, together with the known environmental issues relating to the use of fossil fuels, are expanding the interest in using alternative sources of energy for the production of electricity and heat [1]. The first phase is a transitional period, involving the exploitation of both existing non-renewable and sustainable energy sources connected to an active network [2]. The existing passive network consists of large production units, networks and users. The aim of the production units is to continuously provide the required quantity and quality of electrical power (frequency and voltage) [3]. The future development of energy systems will see the more widespread use of renewable energy sources, which will require a significant change to the structure of future electricity networks [4], [5]. Power production from renewable energy sources usually depends on the local weather conditions and is only partially predictable. The resulting fluctuations in supply are not negligible and have a significant impact on the stability of the entire energy system [6]–[9]. Due to the partial unpredictability of the power supply, an appropriate technology for energy storage should also be included in the system [10], [11]. In this respect, hydrogen technologies are very suitable, because of their wide range of applications [12]. A complex energy network, such as a system for energy supply, storage and consumption, requires advanced planning [13]. In the process of planning, the following facts should be taken into consideration:

- energy source (sort, time and quantity availability),
- energy consumer (time and quantity-dependent consumption),
- energy production units (efficiency, regulation, operating properties),
- economic background and effects on the environment.

Several different program codes have been developed for the simulation, analysis and optimization of energy systems. According to a review of these codes [14] and the requirements for our research work, some limitations of the existing tools were found in all cases [15]. Therefore, the decision to develop a custom-made numerical model was taken. This model is able to simulate the operation of different configurations of energy systems with regards to energy consumption and the available energy sources. The modelling was done with MathWork's Simulink software, which meets all the requirements of the research [16], [17].

II. Energy system

The goal of the presented research was to develop a method for finding the optimal system configuration that satisfies the given requirements and takes into consideration the specific boundary conditions. The method itself should be as general as possible in order to provide applicability to a broad range of different combinations of energy requirements and energy availability. A scheme of the method's idea is depicted in Figure 1, where the procedure is divided into several steps.

1. step: definition of the energy consumers that can require various forms of energy – electrical energy, heat and/or a secondary form of energy, e.g., hydrogen. In general, the energy consumption is dynamically varying.

2. step: definition of the available energy sources with respect to the actual geographical location of the consumers or the energy system. The energy sources can be conventional (natural gas, gasoline, etc.) and renewable (sun, hydro, wind, wood, biogas, etc.).

3. step: selection of the particular energy-system configurations that will be analysed.

4. step: selection of the decision parameters that will be used to find the optimal configuration from the analysed ones. The decision parameter can be the levelized cost of energy, the renewable fraction, the operating and maintenance properties, and the initial cost.

5. step: simulation of the selected system configurations and comparison of the decision parameters. The optimal configuration is selected based on the results of the system simulations using the weighted-sum method (WSM) [27].

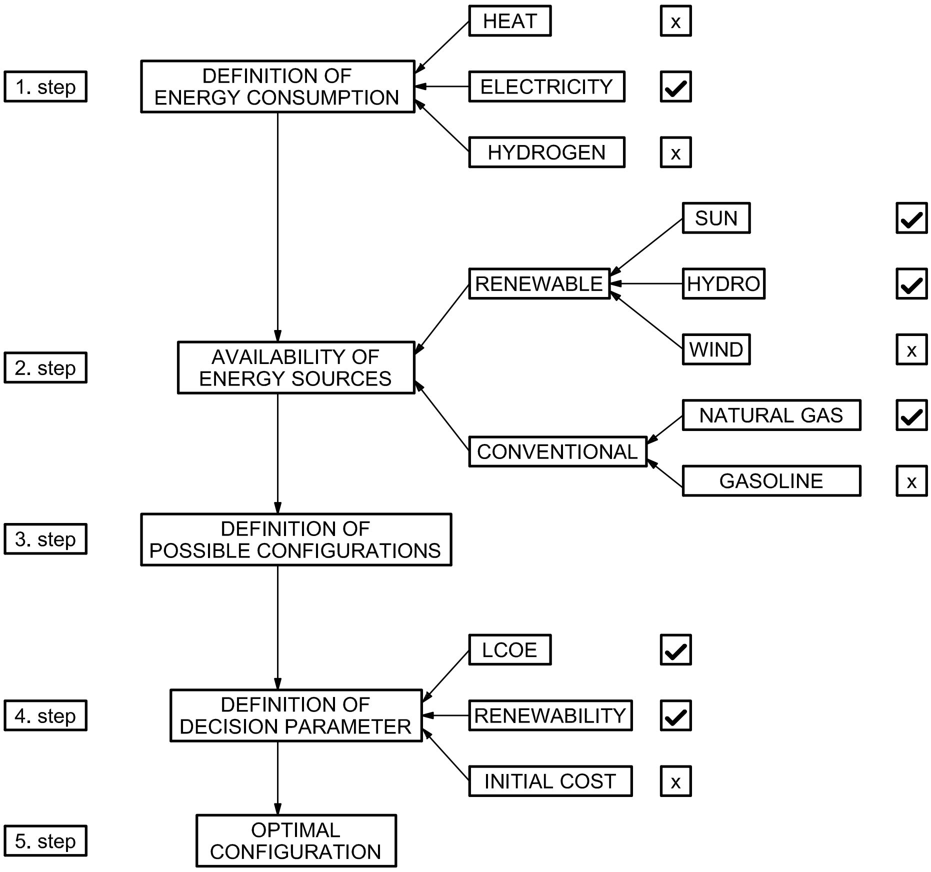

Figure 1: Energy-system design procedure

III. Energy-system configuration (steps 1 to 4)

The applicability of the presented numerical approach to design an efficient energy system is shown in a test case. The energy system, schematically shown in Figure 2, consists of an energy consumer, energy-production facilities (a photovoltaic power plant, a hydroelectric power plant and an internal combustion engine), energy-storage capacities (a battery) and the control.

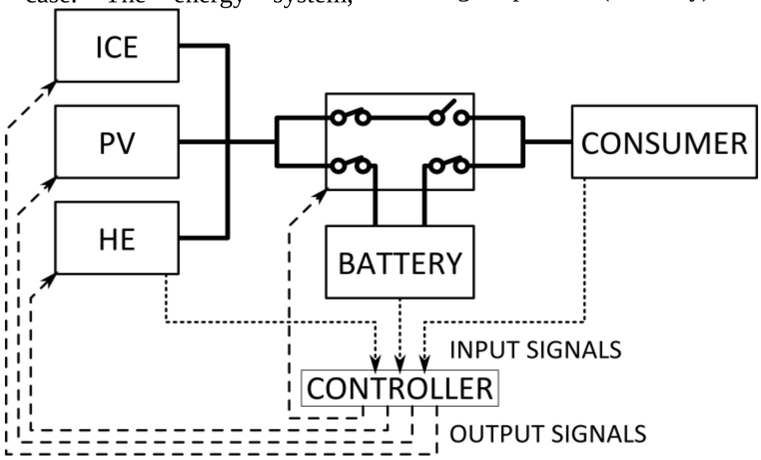

Figure 2: Test-case energy-system configuration: PV is a photovoltaic power plant, ICE is an internal combustion engine, and HE is a hydroelectric power plant

3.1 Energy consumer (step 1)

The electrical energy consumer with a dynamically varying load in the presented case is a village with a typical daily operation through one week [18]. The given weekly load of the observed system is shown in Figure 3.

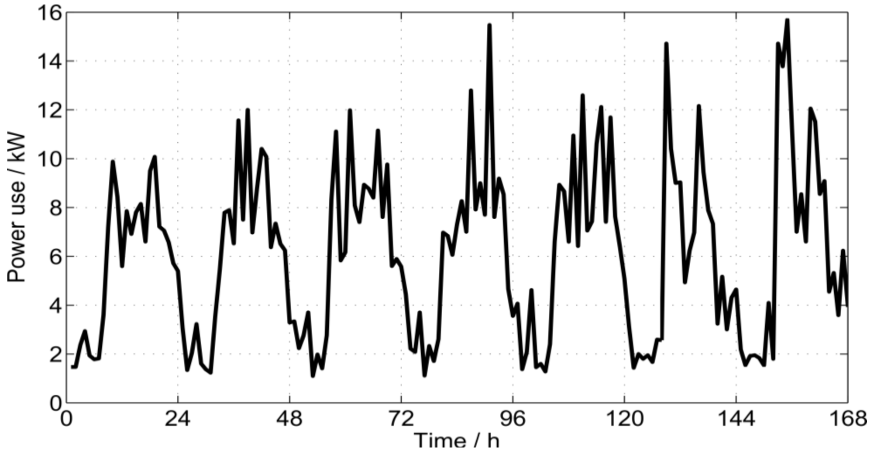

Figure 3: Diagram of the electrical energy consumption

3.2 Energy sources (step 2)
3.2.1 Photovoltaic power plant

A photovoltaic (PV) power plant model [19] represents the renewable energy supply. Its energy output is limited by the area S, the efficiency η_{PV} and the position of the photovoltaic modules, the geographical location and the date, time and weather conditions.

$$P_{PV} = I \cdot S \cdot \eta_{PV} \quad (1)$$

The direct solar radiation I that defines the available energy can be calculated as

$$I = I_0 \cdot \cos\theta \cdot \exp\left(-\frac{T_L}{0.9 + 9.4 \cdot \sin\beta_S} \cdot \frac{p}{p_0}\right) \quad (2)$$

The symbol I_0 is the initial solar radiation, the angle θ is the illumination angle that depends on the geographical location, the date and the time, β_S is the elevation angle of the modules, p is the actual ambient pressure, while p_0 is the normal pressure (1.01325 bar) and, finally, the parameter T_L depends on the weather conditions and is described in Table 1.

Table 1: Weather conditions

Weather	Parameter T_L [-]
Clear and cold	2
Clear and warm	3
Sultry, cloudy	4–6
Rainy	>7

Actual measured values (as shown in Figure 4) were used to describe the power production from the photovoltaic power plant [20]. The initial costs for the PV power plant of 1800 €/kW$_p$ were taken into consideration during the analysis [21].

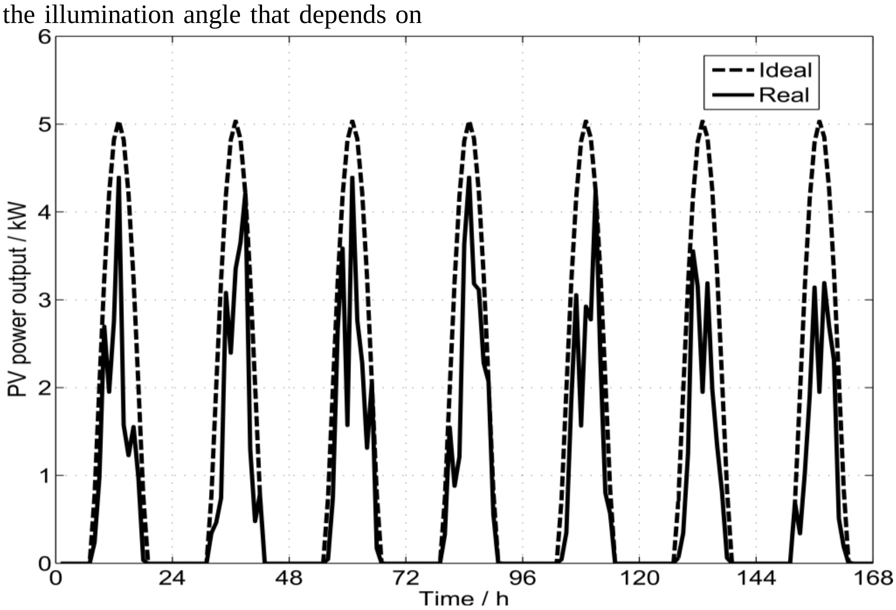

Figure 4: Diagram of the PV power plant's production

3.2.2 Hydroelectric power plant

The hydroelectric (HE) power plant is the second renewable energy supplier. The conversion of the potential energy of the water into electrical energy [3] gives the output power P as a function of the water flow rate $\dot{m}$, the available head h and the overall plant efficiency η_{HE}, which also depends on the mass flow and the head.

$$P_{HE} = \dot{m}\, g\, h\, \eta_{HE} \quad (3)$$

The hydroelectric power plant has an accumulation reservoir to provide a more stable energy supply and to cover the peak power demands. The test case HE power plant was equipped with a Banki turbine that has a nominal flow of 0.2 m^3/h, a maximum available height of 5 m and a constant efficiency of 0.75. The dynamics of the mass of flowing water was provided by measurements [22].

The initial cost of a small hydroelectric power plant [23] depends on the nominal power P and the available hydraulic head h.

$$C_{\mathrm{i}} = 25000 \cdot \left(P[\mathrm{kW}] / h[\mathrm{m}]^{0,35} \right)^{0,6} \quad (4)$$

The operating and maintenance costs C_{om} are estimated at €600 per year.

3.2.3 Internal combustion engine

An internal combustion engine (ICE) with a power generator is the conventional energy source in the observed system that is able to provide a stable energy supply. It has a limited capacity that is considerably smaller than the peak load of the consumer. Also, the lowest output capacity is limited due to the decreased efficiency of the engine. The produced electrical power depends on the supplied heat flow $\dot{Q}_{\mathrm{f}}$ and the efficiency of the electricity production η_{el}.

$$P_{\mathrm{ICE}} = \dot{Q}_{\mathrm{f}} \cdot \eta_{el} = \dot{m}_{\mathrm{f}} \cdot H_{\mathrm{f}} \cdot \eta_{el} \quad (5)$$

The parameter H_f is the calorific value of the used fuel. The initial cost of 1150 €/kW was taken into consideration during the analysis for the internal combustion engine [24]. The operating and maintenance costs C_{om} are €400 per year.

3.2.4 Batteries

Batteries are used to store the excess energy and to supply the peak-load energy. In situations when the production units are unable to cover the power demand, the consumer is supplied with additional energy from the batteries. On the other hand, when the power demand is small, production units can store the excess energy in the batteries. The re-used power $P_{re\text{-}use}$ is considerably smaller than the charging power P_0 due to the charging efficiency η_{in} and the discharging efficiency η_{out}.

$$P_{\mathrm{re-use}} = \eta_{\mathrm{in}} \cdot \eta_{\mathrm{out}} \cdot P_0 \quad (6)$$

The initial cost for energy-storage capacities of 100 €/kWh was considered for the analysis [15].

3.3 Possible system configurations (step 3)

Five different size variations of the energy system were taken into consideration, as shown and defined in Table 2.

Table 2: Analysed size variations

System code	Photovoltaic power plant [kW]	Hydroelectric power plant [kW]	Internal combustion engine [kW]	Battery [kWh]
P0-H7-I5	0	7	5	15
P5-H7-I4	5	7	4	16
P10-H7-I2	10	7	2	19
P15-H7-I1	15	7	1	21
P20-H7-I0	20	7	0	22

The sizing of the particular production facilities was chosen during the optimisation process. The particular system components were set up for the specific power consumer, considering the following:

- A stable and secure energy supply throughout the entire operating period.
- The operation of particular production facilities (i.e., weather conditions, water level in the accumulation reservoir, charging and discharging of the battery).
- The minimum sizes of particular production facilities with regards to the initial capital.

- The maximum utilization of the renewable source of energy.
- The minimum operating costs and the levelized cost of the electricity.

During the analysis the following results were taken into consideration:

- Operating diagrams (one-week scale) for all the production facilities of the system.
- Levelized cost of electricity (LCOE).
- Renewability factor (RF), which is the ratio between the amount of electricity produced from the renewable energy sources and the total amount of produced electricity.
- Electricity consumption production ratio (CPR), which shows the required oversize of the energy system due to energy storage, where the output energy is smaller than the input energy.

3.4 Decision parameters (step 4)

3.4.1 Levelized cost of electricity

A stable system operation should not be the only monitored parameter when selecting 'the best' configuration for the system. Financial aspects have a great (if not the greatest) influence on the energy system's planning, too. The information that predicts the viability of an individual power plant is its own levelized cost of electricity. This includes the initial capital costs, the costs of operation, the maintenance, the fuel as well as the environmental taxes and the costs for system decommission [3].

The initial cost C_i of a particular power plant is a product of the specific initial costs c_i and the nominal power of the system P.

$$C_\mathrm{i} = c_\mathrm{i} \cdot P \tag{7}$$

The annuity factor a depends on the investment period n and the interest rate r.

$$a = \frac{r \cdot (1+r)^n}{(1+r)^n - 1} \tag{8}$$

The annual fixed costs C_a are thus

$$C_\mathrm{a} = C_\mathrm{i} \cdot a \tag{9}$$

The total costs are the sum of the annual fixed costs C_a, the operating and maintenance costs C_om and the fuel costs of the internal combustion engine C_f. The levelized cost of electricity (LCOE) is defined by the ratio of the total costs and the produced energy E_prod.

$$LCOE = \frac{C_\mathrm{a} + C_\mathrm{om} + C_\mathrm{f}}{E_\mathrm{prod}} \tag{10}$$

3.4.2 Renewability factor

The renewability factor (RF) could be the next decision parameter during the process of finding an optimal system configuration. This factor shows how 'green' is a particular solution and is presented as the ratio between the amount of electricity produced from renewable energy sources and the total amount of produced electricity.

$$RF = \frac{E_\mathrm{prod,renew}}{E_\mathrm{prod,tot}} \tag{11}$$

3.4.3 Electricity-consumption production ratio

The electricity-consumption production ratio (CPR) shows the amount of energy lost through the storage capacities. The output of the storage capacities is smaller than the input due to its charging and discharging efficiency.

$$CPR = \frac{E_\mathrm{cons,tot}}{E_\mathrm{prod,tot}} \tag{12}$$

IV. Finding the optimal system configuration (step 5)

To test the observed system's operation with predefined parameters and rules a numerical model of the system was set up using MathWork's Simulink software [25], while Matlab was used to analyse and present the results.

The numerical model of the energy system was given a typical one-week time series of power consumption (Figure 3). The response of the observed production facilities was observed. The main task of the control unit was to supply a sufficient amount of power to cover the current load by starting and stopping particular units with respect to other parameters.

4.1 System stability and control

The entire energy system is controlled with a system-state matrix approach [26]. The control unit monitors particular parameters, in the observed case the current power consumption P, the available hydraulic head h and the stored energy in the batteries C. Each possible combination of monitored parameters represents a system state S_{xyz}(x = 1...i; y = 1...j; z = 1...k) in a particular time step and, mathematically speaking, the cell of a 3D-matrix, as shown in Table 3 and Table 4. The matrix cells include lists of instructions for all the elements in the system describing how to optimally respond to the particular situation. Particular responses are shown in Table 5.

Table 3: Possible system states regarding the monitored parameters for lower power use

(P =< 5 kW)		Available height / m		
		$h < h_{min}$	$h_{min} \le h \le h_{max}$	$h \ge h_{max}$
Stored energy / kWh	$C < C_{min}$	R_1	R_7	R_3
	$C_{min} \le C < C_{max}$	R_4	R_4	R_5
	$C \ge C_{max}$	R_6	R_6	R_6

Table 4: Possible system states regarding the monitored parameters for lower power use

(P > 5 kW)		Available height / m		
		$h < h_{min}$	$h_{min} \le h \le h_{max}$	$h \ge h_{max}$
Stored energy / kWh	$C < C_{min}$	R_1	R_1	R_2
	$C_{min} \le C < C_{max}$	R_4	R_4	R_3
	$C \ge C_{max}$	R_6	R_6	R_6

Table 5: Definition of particular responses

	PV	ICE	HE
R_1	M	M	O
R_2	M	M	M
R_3	M	R	M
R_4	M	O	O
R_5	M	R	F
R_6	F	O	O
R_7	M	R	O

O – turn off
M – maximum output
R – retain previous load
F – follow power consumption

The controller also has to take into consideration the limitations and operating properties of a particular energy-production facility. The basic operating constraints of the observed test case of an energy system are:

- Dynamically varying power consumption represents the village's demand that is covered by the photovoltaic power plant, the hydroelectric power plant, the internal combustion engine and the batteries.
- The photovoltaic power plant's production depends on the weather conditions. The produced energy is primarily used directly to cover the consumers' energy demands. On the other hand, when the produced energy exceeds the consumption, it is used for battery charging. When the battery is fully charged, the production of energy is reduced to the current power consumption.
- The hydroelectric power plant's operation depends on the river's mass flow and the water level in the accumulation reservoir. In the case of a high water level the produced energy is used to cover the energy demand and for the battery charging. If the water level in the accumulation reservoir is too low, the power production is stopped due to the smaller overall efficiency for the low hydraulic head.
- The internal combustion engine's operation is included in the system as a back-up to avoid the breakdown of the energy supply. When the energy from the renewable sources and the batteries is insufficient for the current energy demand the engine starts to operate. The engine operates in situations when the battery charge level and the accumulated water level are low. It operates with the maximum power to cover the energy demand and to charge the battery to a charge level of 50 %. This kind of operation avoids low-efficiency operation and frequent start-ups.
- The battery's basic purpose is to provide a stable and constant energy supply. When there is an excess of produced energy, it is stored in the battery for a time when there is a deficit of energy.

4.2 Optimization

The optimal configuration is selected based on the results of system simulations using the weighted-sum method (WSM) [27]. The particular decision parameters $f_{dp,i}$ are weighted with respect to the investor's interests $m_{dp,i}$ (1 to 5, where 1 is not important and 5 very important).

$$A_{WSM,\,opt} = MAX\left(\sum_{i=1}^{n} f_{dp,i} \cdot m_{dp,\,i}\right) \tag{13}$$

4.3 Results

The analysis included five different size variations with three primary energy sources (solar, hydro, natural gas), as shown in Table 6.

Table 6: Comparison of the results

System code	PV	HE	ICE	Battery	FRE	LCOE	RUP	Initial cost
	[kW]	[kW]	[kW]	[kWh]	[-]	[€/kWh]	[-]	[€]
P0-H7-I5	0	7	5	15	0.737	0.25	0.924	**62,800**
P5-H7-I4	5	7	4	16	0.875	**0.236**	0.935	70,750
P10-H7-I2	10	7	2	19	0.919	0.244	0.932	77,750
P15-H7-I1	15	7	1	21	0.953	0.258	0.938	85,800
P20-H7-I0	20	7	0	22	**1.000**	0.268	0.943	93,750

The optimal configuration can be determined according to a defined decision parameter. If the decision parameter is the initial cost, the first variation (P0-H7-I5) is the optimal configuration. If we choose the highest factor of renewability, the last variation (P20-H7-I0) is the optimal configuration. Finally, considering the LCOE, which has the largest influence, the second variation (P5-H7-I4) is the optimal configuration.

Overall, the decision parameters (FRE, LCOE and initial cost) were defined and valued as very important ($m_{dp,i}$=5) in order to determine an optimal configuration. The configuration P5-H7-I4 was found to be the optimal configuration on the basis of the valued decision parameters. The operation of this system configuration is presented in Figure 5. The energy system operates in such a way as to exploit the renewable sources as much as possible. The photovoltaic and hydroelectric power plants operate to cover the energy demand and to charge the battery, when possible. When there is not enough produced and stored energy, the internal combustion engine starts operating. When a specified level of stored energy in the battery is reached the production facilities just follow the power-demand dynamics.

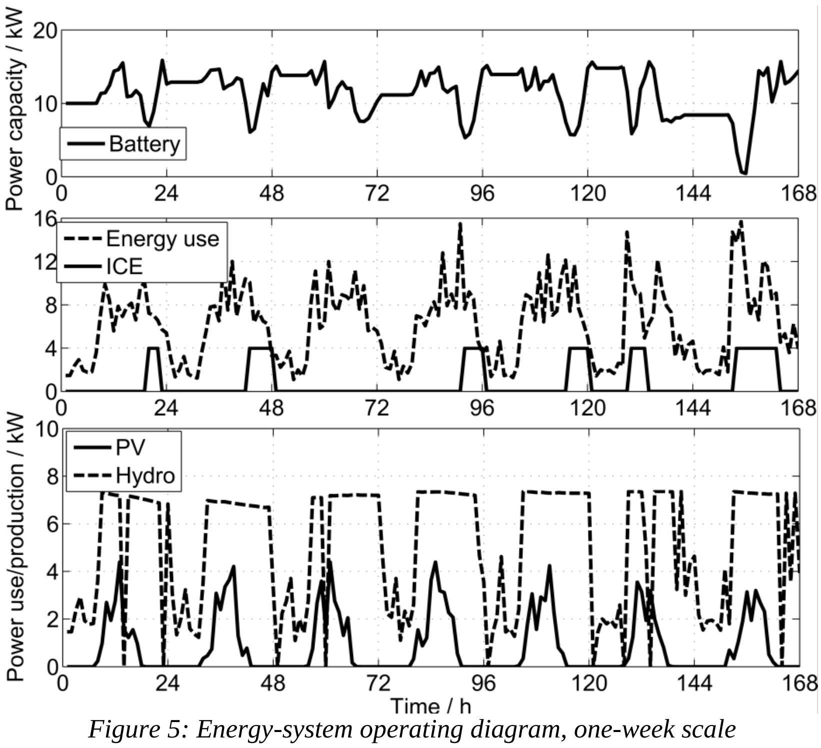

Figure 5: Energy-system operating diagram, one-week scale

The excess water energy is stored in an accumulation reservoir in the form of potential energy. The hydroelectric power plant can operate with water levels above a specified minimum and at the same the water level rises, Figure 6.

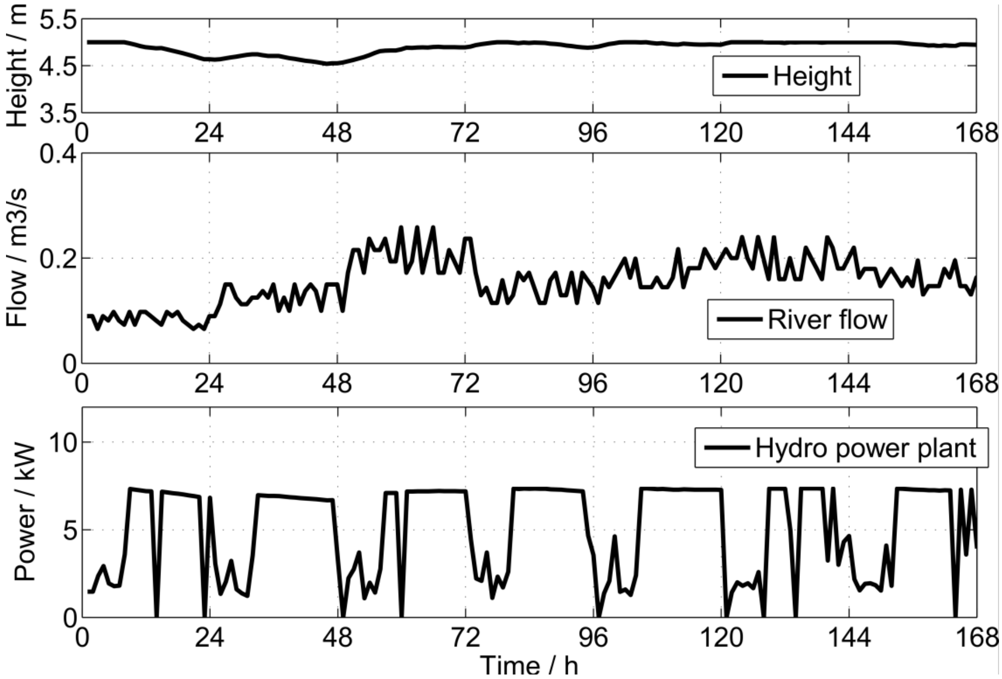

Figure 6: HE operating diagram, water flow and accumulation height, one-week scale

The operating diagrams represent a stable supply of energy in a self-sufficient energy system with a maximum exploitation of renewable sources. The operation of individual units is coordinated as well due to a precise and accurate control unit. The accuracy is shown in constant operation with a low frequency of start-ups and stops. In the case when different operating responses are defined, the operation of the energy system would lead to an unstable and irrational state. Therefore, the calculation of the decision parameters could bring another, wrong, optimal configuration.

V. Conclusion

In this paper a description of a numerical approach to designing an energy system is presented, where a five-step energy-system design procedure has been developed. The applicability of the developed procedure was demonstrated on a test case. The particular production units of the system were individually modelled (i.e., the photovoltaic power plant, the hydro power plant, the internal combustion engine and the storage capacities). The energy system was controlled using a system-state matrix approach. The testing of the design procedure and the numerical modelling of the described energy system were performed with Mathwork's Simulink code. Using system simulations, the optimal configuration of a self-sufficient energy system and its regulation can be found by considering different criteria or decision parameters. The selection of the decision parameters presented is very important since the choice of these decision parameters usually results in a completely different optimal output system. The results and conclusions of this test-case simulation cannot be generalized because of its specific input parameters, most notably the decision parameter. On the other hand, the principle of using a numerical approach for designing an energy system can be generalized and used for even more complex systems, where other approaches are not as transparent and straightforward.

Future work guidelines point to the further modelling of different structures of the energy system (such as wind turbine, CHP unit, fuel cell, etc.) and setting up particular control systems.

VI. Acknowledgement

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