On Defining and Assessing of the Energy Balance and Operational Logic Within Hybrid Renewable Energy Systems

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Abstract. The paper is considering a problem of providing energy in small neighbourhoods consisting of the households and local industrial or commercial units (e.g. farms, workshops, offices). Such communities may benefit from the use of the Hybrid Renewable Energy Systems (HRES) harnessing solar and wind power, accumulating excess energy using Power Storage Banks and integrating to the External Power Grid (EPG). Phases of planning, design, installation and operation of HRESs are considered as interconnected complex tasks needing appropriate Requirement Analysis. Architecture and energy balance of the HRES are introduced where important role is devoted to the Energy Gateway Station. Characteristics of the exploiting of solar and wind potential energy and customer usage patterns in such communities are considered. Types of requests for energy use or its supply to EPG as well as principles of the operational logic of the HRES are introduced. Criteria for assessing of the effectiveness of HRES are briefly discussed.

Keywords: Renewable energy sources · Hybrid renewable energy system · System architecture · Energy balance · Operational logic · Energy potential assessment · Decision support system

1 Introduction

Present rate of all the energy consumption is growing very fast. Nowadays there is growing interest to development of the renewable energy sources (RES) in the energy supply chain. Various forms of RESs using solar and wind energy are proposed. Solar energy has a huge potential of $1.8 \times 10^{1}1$ MW [1], which is many times larger than total energy consumption of the world. Assessing of the wind energy potential is much more difficult and depends on the location. For example average wind speed in different countries onshore may vary from 1.8 to 4.3 m/s [2].

Current stage of development of the RESs in Ukraine was considered in [3]. The focus of our research is on defining general architecture and its operation rules for Hybrid RESs (HRES) having both renewable energy sources as well as access to the External Power Grid (EPG). Such HRESs will be used in small localities which are very sensitive to the costs of the energy. In such approach significant number of

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consumers will produce energy for their own needs as well as may send surplus to the external grid. Such implementation decreases energy losses during transportation as generators are situated next to consumers.

Planning, design, installation and operation of HRESs are all complex tasks and shall be performed phase by phase and considered in total context from Request to Energy:

Planning(Request,Requirements,TP) =>
Design(Requirements,Drawings,TD) =>
Installation(Drawings,System,TI) =>
Operation(System,Energy,TO)

Here *Request* (formal or informal) is input to the *Planning* phase and has to be translated to the *Requirements* during *Planning Time TP*. *Design* phase is accepting *Requirements* and has to produce *Drawings* (a set of installation technical documentation) during *Design Time TD*. Similarly, *Installation* phase is producing working *System* during *Implementation Time TI*. Operating *System* is producing *Energy* during *Operation Time TO*.

Operation characteristics of the target HRES are pretty much defining steps of planning, design and installation. Thus, as in many other cases of dealing with complex systems, we have to start from the *Requirement Analysis*. Having clear targets defined in the requirements will allow to translate them to the operational parameters and this will enable modeling of the system with appropriate tools before starting of the design. Thus, it may be convenient to use Decision Support Systems (DSS), which can take on some the user's tasks. The architecture of such DSS is presented in [4].

The rest of the paper is organized as follows. Section 2 is presenting architecture and energy balance of the HRES in a small neighbourhood. Section 3 is devoted to characterization of the energy usage and generation in a small neighbourhood. Operational logic of the requests for energy use or supply is considered in Sect. 4. Section 5 is considering criteria for evaluation of the HRES. Conclusions are drawn in the Sect. 6 and followed by the discussion of the future work.

2 Architecture and Energy Balance of the HRES in a Small Neighbourhood

It is assumed that the legal entity operating HRES (*HRES Community)* is defining its operational goals, policies, etc. HRES Community is responsible for the costs incurred as a result of designing, installing and operating of the HRES as well as for obtaining, exploiting and sharing benefits/profits to its members.

Figure 1 depicts typical architecture of the HRES in a small neighbourhood comprising of the few households with possible commercial/industrial activities (farms, workshops, etc.). Here energy is generated using *sources* such as Photovoltaics (PV) elements (Solar Panels) installed on the roofs of the houses or nearby land (denoted as Es energy) and Wind Turbines installed where it is suitable (denoted as Ew

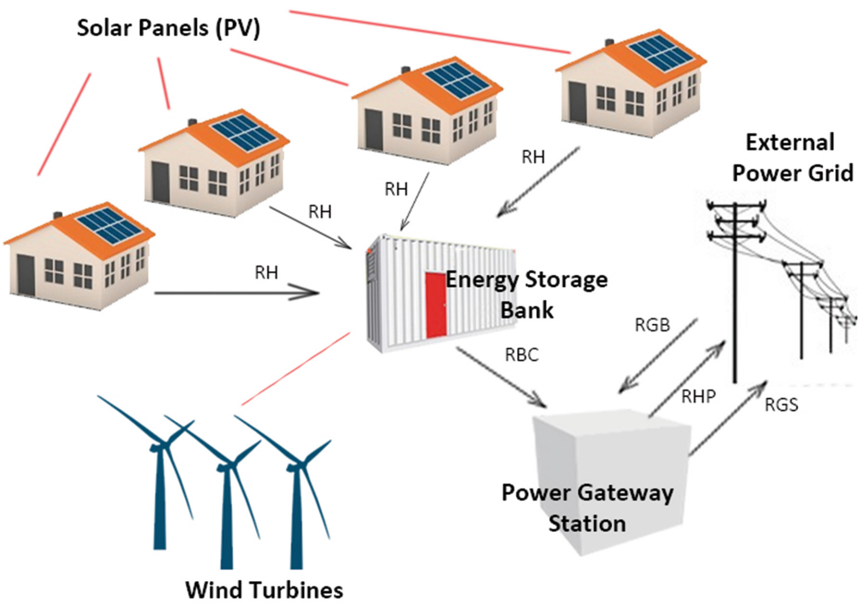

Fig. 1. Architecture of HRES in a small neighbourhood

energy). Energy is *stored* in the Energy Storage Bank (ESB) for the future use (denoted as Eb energy when used or Ebc when charged).

Additionally, HRES is connected to the External Power Grid (EPG) which can be serving as both a *source* of the additional purchased energy (denoted as Egp energy) and a *sink* to where surplus energy could be *supplied* and potentially *sold* for a certain *price* (denoted as Egs energy). EPG is assumed as *existing power network* belonging to the *EPG Operator*. It requires installing of the *Power Gateway Station (PGS)* which provides routing of the energy in and out of the HRES as required.

Total energy balance in the HRES is shown in Fig. 2. Here are defined energy requests as well as sources and parameters influencing need to purchase or opportunity to sell energy.

RH := SUM(1..N, Rhi)	-- Current ∑ of Rhi requests from N households
0 ≤ Es ≤ Esmax	-- Current solar energy Es is between 0 and Esmax
0 ≤ Ew ≤ Ewmax	-- Current wind energy Ew is between 0 and Ewmax
0 ≤ Ebmin ≤ Eb ≤ Ebmax	-- Current PSB capacity Eb is between Ebmin and Ebmax
Ea1 := Es + Ew	-- Current available solar and wind energy
Ea2 := Ea1 + Eb	-- Current available solar, wind and battery energy
Erp := RH —Ea	-- Current deficit of energy
Esale-max := Ea2 - RH	-- Current maximum energy for sale to EPG
0 ≤ Esale ≤ Esalemax ≤ Eo	-- Energy for sale to EPG is between 0 and Esalemax and is
	-- limited by maximum out line capacity Eo

Fig. 2. Total energy balance in the HRES

3 Characterization of the Energy Usage and Generation in a Small Neighbourhood

Although the sun and wind are an inexhaustible source of energy, but their disadvantage is the stochastic nature of the flow of energy, depending on the season, time of day and weather conditions. From the other side, the energy needs of consumers also have a random character that is not dependent on the electricity generation. Thus, defining energy consumption and generation patterns in the HRES is essential for producing Requirements for the Design as well as for setting modeling and simulation parameters in the Decision Support System.

3.1 Energy Usage Characteristics

As an example and for further verification and implementation, it was decided to make first studies for Sumy area, Ukraine, as a place where research is conducted. In future this model is going to be general and can be used for any region.

Figure 3 shows example of the energy usage for December 22, 2015 which was selected as the longest day of the year during which it was required the highest amount of electricity for lighting of the house as well as it is the shortest light day which directly affects output of the solar panels. Thus, this date is representing the worst operating conditions for PV sources and simultaneously the heaviest energy demand. These data are obtained from the local energy company Sumyoblenergo [5] and are representative for a typical private house in Sumy area, Ukraine. From this graph it is clear that used energy was fluctuating between minimum 3400 (at 04:00 and 05:00) and maximum 7350 (at 22:00) Watts and the average request from household was 5380 W.

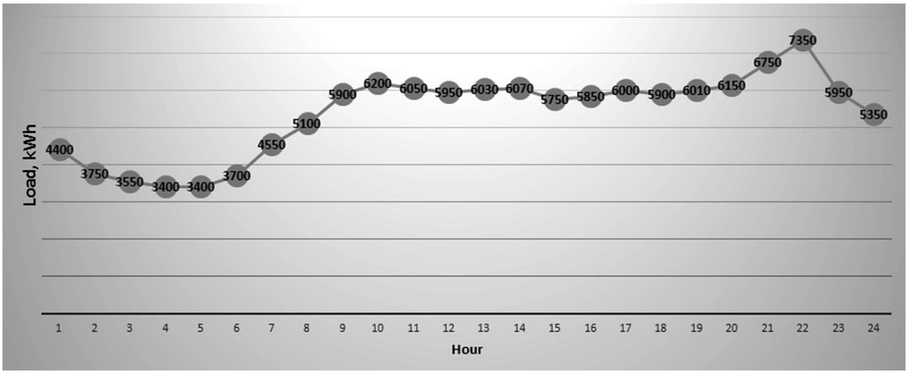

Fig. 3. Energy consumption during 22 December, 2015 in the private household in Sumy area

Power of electrical load required by the consumers is represented by the probability-statistical model which defines the daily schedule of the design load of the object for each day of the year P_{pi} as follows

$$P_{pi} = \overline{P_i} \times P_{max} \times (1 \pm \beta \times \sigma(P_i)) \times K_c \quad (1)$$

where $\overline{P_i}$ – the expectation of the load at the time i, P_{max} – maximum load, β – the reliability coefficient, σ – mean square deviation, and Kc – seasonality factor.

3.2 Energy Generation Characteristics

Suitability of the solar and wind energy sources very much depends on the *geographical location* and *climate conditions*. Energy generation depends on the following factors:

- Amount of the solar radiation in the given time of the day in the given day of the year in the given point on the Earth surface depending on sun position on the sky - defines daily cyclicity of the sun radiation and as a result *cyclicity* and *volume* of a power generated by the PV components;
- Weather and season conditions affecting amount of solar radiation and strength/direction of the wind – defines *variability* of generated energy;
- Total number and power of the individual generation components (PV panels/wind turbines) – defines *maximal possible outputs* in each time *t*;
- Periodical (planned) maintenance of the components (cleaning, tuning, servicing, replacing, etc.) – defines *periodical (planned) reduction* of the generated power;
- Occasional outages of the components requiring repairs or replacements – defines *unplanned reduction of the generated power*.

3.3 Assessment of the Solar and Wind Energy Potential

In [6] it is suggested top-down approach to estimate energy amount in the region which we apply for both solar and wind energy.

Available solar energy potential Esa is expressed as the physically available solar radiation on the earth's surface, which is influenced by various factors. The estimated potential is then reduced by considering technical limitations (e.g. conversion efficiency factors), which means taking into account the losses are associated with the conversion of solar irradiation to electric power or heat by state of the art technologies (Est). Additionally there are soft factors which may be modified over time and may vary regionally (e.g. acceptance of technology, legislation) and the potential is further reduced to realizable energy Esr. Thus,

$$\text{Esr} < \text{Est} < \text{Esa} \quad (2)$$

Estimated value of solar radiation available to PV panels is usually assumed for the region, but we are proposing to do more precise calculation and divide area to zones. For doing this it is necessary to obtain meteorological data based on hourly values inflow of solar radiation on an inclined surface and hourly values of ambient temperature.

The value of solar radiation Gtilt is considered as a function:

$$G_{tilt}(\varphi,\omega,\gamma,s,N) = (G_{dir}(\varphi,\omega,\gamma,s,N) + G_{dif}(\varphi,\omega,s,N)) \times (1 - a + 0{,}38 \times n) \times n \quad (3)$$

where *Gdir* – direct solar radiation, *Gdif*– diffuse solar radiation, φ – latitude location, ω – the angular displacement of the sun, depending on the time of day, s – platform tilt angle to the horizon, γ – plane azimuth angle, n – the value of cloudiness, a – coefficient depending on the type of terrain, N – the number of a day in year.

For each day in a year we use probability-statistical model to define the value of cloudiness which may produce geographical restrictions for the installation of solar energy systems and affect choosing suitable areas.

For estimation of exploitable solar potential it is planned to use data on parameters which are specific to the PV panel $E_s(t)$ at the time t:

$$E_s(t) = n_{pv} \times A \times G_{tilt}(t) \quad (4)$$

where A is a size of the area of solar panels, n_{pv} – efficiency coefficient specific to solar panel, *Gtilt(t)* – hourly values inflow of solar radiation on an inclined surface.

According to [7] n_{pv} depends on energy conversion efficiency of solar panel, energy conversion efficiency of maximum power point tracking system (MPPT), temperature coefficient of solar panels, solar panel temperature under standard measurement conditions and the actual temperature of the solar panel.

For identifying wind energy is used the following top down approach. At the first level, the potential energy is limited by all the physical geographical, socio geographical and land constraints which leads to the estimation of the theoretical energy. Here are used statistical models and interpolating techniques to determine the average wind speed as a basis to choose location. Also we determine the most common wind direction to give advices on installation specification of wind turbines.

The theoretical energy can be further limited by the characteristics of the commercially available wind turbines and the constraints of a wind farm.

Finally, the exploitable energy at the time t is defined as follows

$$Ew(t) = 0{,}5 \times \rho \times A \times C_p(\lambda) \times V_w(t)^3 \quad (5)$$

where ρ - air density, A – area size of rotor, $C_p(\lambda)$ – dependence coefficient of efficiency of selection wind power, which depends on the design features of wind turbines and its rapidity λ, and wind speed $V_w(t)$.

4 Operational Logic of the Requests for Energy Use or Supply

According to the suggested HRES architecture requests for energy use or supply within HRES or between HRES and EPG could be as follows:

- RH: requests from individual households to HRES for satisfying domestic/industrial use (i.e. total sum of the Rhi);
- RBC: from PSB to HRES/PGS/EPG for recharging;
- RHP: from HRES via PGS to EPG for purchasing Egp energy for satisfying domestic/industrial use (i.e. in a case of low Es + Ew/Es + Ew + Eb power);
- RGS: from the HRES via PGS to EPG for selling of the surplus energy;
- RGB: from the EPG via PGS to HRES for buying of the surplus energy.

We assume that power requests are coming as random sequences of events. Each type of request RHi/RHPi/RBCi/RGBi/RGSi in general is characterized by its discrete Time Ti, finite Time Length TLi, finite Energy Ei associated with the request (power volume), Priority Pi and Cost Ci.

$$\mathrm{RHi/RBCi/RHPi/RGSi/RGBi} = (\mathrm{Ti},\ \mathrm{TLi},\ \mathrm{Ei},\ \mathrm{Pi},\ \mathrm{Ci}) \tag{6}$$

Operational logic of HRES is presented in Fig. 4. Here for simplicity are omitted instant discrete values of times, requested powers, priorities as well as costs and only generalized value of RH is used. Also, conditions such as “UNTIL Tx = 0” shall be understood as repeated generation of the request during specified period of time. Obviously, end users are not expected to generate their Rhi with attached time limit TL. It is rather a task for HRES control system to set suitable values for the TL intervals during which energy could be purchased from EPG. This means that in the situation when there is not enough Ea to satisfy total RH there could be generated repeated RPHi until either Ea or RH are changed and the need for purchasing is expired.

It is important to introduce the logic for purchasing and selling of the energy from/to EPG into the overall operating scheme of the HRES right from the design phase because adding it later to the live system could be problematic. As a temporary

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REPEAT
GET(RH)                                   -- Get total energy request
IF (Eb ≤ Ebmin) OR                        -- If battery low OR
        ((Ebmin < Eb < Ebmax)                     -- battery good
                AND (RH=0))                               -- AND no other requests
        THEN (RBC(Ec,HRES);                       -- then generate charging request
        RH := RH + Ec)                            -- and adjust total request RH
Ea := Ea1 – SOLD(EPG)                     -- Available power minus already sold
IF RH ≤ Ea THEN USE(Ea,RH)                -- If enough then use Ea to satisfy RH
IF RH > Ea THEN Ea := Ea + Eb             -- If not enough then add battery
IF RH ≤ Ea THEN USE(Ea,RH)                -- If enough then use Ea to satisfy RH
IF RH > Ea THEN RHP(RH-Ea,Tp,EPG)         -- If not enough then request RH-Ea
IF RHP(OK) THEN BUY(RH-Ea) UNTIL Tp=0     -- If OK then buy extra RH-Ea during Tp
IF Ea > RH THEN RGS(Ea–H,Ts,EPG)          -- If ∃ surplus then offer it to sell during Ts
IF RGS(OK) OR RGB                         -- If sell accepted or ∃ request for surplus
        THEN SELL(Ea–RH) UNTIL Ts=0               -- then sell surplus to EPG during Ts
IF CHARGING(FINISH) THEN RH:= RH–Ec       -- If charged then adjust total RH
UNTIL STOP
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Fig. 4. Pseudocode for operational logic of the HRES

measure some fixed default prices can be allocated per energy unit (e.g. KWh) which can be later on assigned to the realistic floating market values.

5 Criteria for Evaluation of the HRES

Effectiveness of the system is usually evaluated by looking at its performance and cost. In the case of HRES it is suitable to use non-interrupted power supply to the customers, Deficiency of Power Supply Probability (DPSP) and Related Excess Power Generated (REPG) [7] as well as Cost Of Energy (COE) of a separate unit [8–10].

5.1 Evaluation of the Energy Efficiency of HRES

Minimizing of the DPSP and REPG are important targets which should be achieved by the efficient design.

The Deficiency of Power Supply Probability (DPSP) is defined as the sum of the deficit in power generated by HRES (i.e. sum of the requested extra energy) during the given time period as a ratio to the total sum of the energy requests RH:

$$DPSP = \sum\nolimits_{t=1}^{T} RHP(RH(t) - \mathrm{Ea(t)}) \Big/ \sum\nolimits_{t=1}^{T} RH(t) \qquad (7)$$

According to the operational logic (see Fig. 4), if energy generated by HRES exceeds required amount RH(t), then the excess energy is accumulated in the PSB until reaching its maximum value E_{Bmax}. After that these excesses can be sold or, if not sold, wasted.

The Relative Excess Power Generated by the HRES is defined as a ratio of the total excess power generated by the HRES in a given time period to that of the total sum of energy requests RH.

$$REPG = \sum\nolimits_{t=1}^{T} RGS(Ea(t) - RH(t)) \Big/ \sum\nolimits_{t=1}^{T} RH(t) \qquad (8)$$

5.2 Cost Analysis of HRES

Approach to cost analysis of HRES elements and the system as a whole is suggested in [11–13]. The cost of 1 kWh of energy in the output of HRES for one separate object with a particular configuration of elements is the economic criterion which helps to determine system configuration.

The objective function of the optimum design problem is the minimization of COE. COE is an economic evaluation tool for the energy production in integrated system which includes all recurring and non-recurring costs over project lifetime. It is defined as the ratio of the total annualized cost of system (TAC) to the annual electricity production (TALE) by the system.

$$COE = TAC/TALE \tag{9}$$

In opposite to TALE (historical data), the annualized cost of system is the sum of the annualized capital cost $\left(C_{cap}\right)$, the annualized replacement cost $\left(C_{repl}\right)$, and the annualized maintenance cost $\left(C_{maint}\right)$ of all components of system.

$$\text{TAC} = C_{cap} + C_{repl} + C_{maint} \tag{10}$$

Maintenance and replacement cost occur during the project life while capital cost occurs at the beginning of a project.

6 Conclusions and Future Work

A problem of defining and assessing of the energy balance and operational logic within HRESs harnessing solar and wind power for the use within small neighbourhood have been considered in this paper. Novel architecture of HRES, which is accumulating excess energy for the future usage as well as benefits from integration to the External Power Grid (EPG) via Energy Gateway Station is suggested. Total energy balance in the HRES is presented.

Characterization of the energy usage and generation in a small neighbourhood is performed with the focus on assessment of the solar and wind energy potential. Obtaining of data on energy usage in households (such as shown in Fig. 3) is important step for realistic modelling of the HRESs.

Five types of requests related to energy use or supply within HRES or between HRES and EPG are introduced: RH (from individual households for satisfying domestic/industrial power use), RBC (from PSB for recharging), RHP (from HRES to EPG for purchasing extra energy), RGS (from HRES to EPG for selling of the surplus energy) and RGB (from EPG to HRES for buying of the surplus energy). Operational logic of the HRES is presented in a form of pseudocode which is initial step towards formulating functional requirements. Finally, criteria for evaluation of the HRES are formulated and briefly discussed.

Future work requires the following steps:

- Development of the *Power Request and Supply Protocol (PRSP*) within HRES and between HRES and EPG via PGS.
- Detailization of the parameters used in the requests processed by the PRSP (i.e. Time Ti, finite Time Length TLi, finite Energy power volume Ei associated with the request, Priority Pi and Cost Ci).
- Detailization of the functions of the PGS and ESB Control System as relates to the PRSP.

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