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A Mathematical Model for the Estimation of the Energetic Potential for Several Renewable Energy Sources: Application on the Design of a Modern Power Plant

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Abstract. This work presents a mathematical model to support the electrical energy production in a specific area by using Renewable Energy Sources (RES). More precisely, three RES types (namely, wind, solar and hydropower) are considered while biomass is used to satisfy thermal demands. The actual goal of the model is to generate one or more scenarios for the efficient production of electrical energy for a specific area by selecting the most suitable RES in terms of energy efficiency and cost effectiveness. More specifically the decision criteria are the minimization of installation and operational costs produced for each scenario and the maximization of the electrical energy produced by the specific power plant. Finally, feasibility analyses for selected case studies as well as an evaluation against similar best practices are also carried out for each scenario proposed.

Introduction

The diminishing resources of oil, coil and gas, require a fundamental restructuring of our energy systems in the near future since the majority of global energy demands is nowadays mainly covered by such conventional energy sources. Furthermore their use highly affects the environment in terms of emissions and thermal dissipations. Over the last decade, considerable scientific interest has been shown to the exploitation of RES, mainly because they are environmental-friendly and their use does not affect their future availability. The scope of the present paper is to develop a mathematical model for the estimation of the effectiveness of RES used for electricity production. To achieve this effectiveness, wind, solar and hydropower are considered as primary energy sources while biomass is considered as heat generator only. By using the proposed model a potential investor can generate one or more scenarios for the efficient production of electrical energy for a specific area, so as to finally decide which RES type is the most suitable in terms of energy efficiency and cost effectiveness.

Technological issues

Renewable energy technologies transform a renewable energy resource into useful heat, cooling, electricity or mechanical energy. The four significant RES that can be considered as serious alternatives of fossil fuel energy are the wind energy, the solar energy, the hydro-power and the biomass. The technology for direct conversion of solar and wind energy into electricity is currently available (PV and wind-generators, respectively) while the hydropower is widely used during the last century. Finally, biomass has attained significant interest due to its high energetic content, which can be rather easily converted to useful power. It is rather obvious that the characteristics of the renewable resources influence the behavior and economics of renewable power systems.

Solar power technologies convert solar radiation into direct current (DC) electricity by using Photovoltaic modules (PV). The electrical energy produced by a typical PV array is given as [1]

$$E_{solar} = n_{PV} \cdot n_{inv} \cdot G \cdot OR \cdot A_{PV} \cdot K_{PV} \quad (1)$$

It is evident that the critical parameter throughout solar energy is converted to electricity is the amount of solar radiation available for conversion at some location, and how that amount varies over time.
The kinetic energy of the wind that can be captured by wind turbines is highly dependent on the local average wind speed, given as [1]

$$E_{wind} = ED \cdot A_{WT} \cdot n_{conv} \cdot K_{WT} \tag{2}$$

Equation (2) indicates that the power output of wind turbine generator at a specific site depends on wind speed at hub height as well as on the speed characteristics of the turbine.

Hydroelectricity is one of the most mature forms of renewable energy, providing more than 19% of the world's electricity consumption from both large and small power plants. The ability of falling water to produce power depends on the flow rate and the vertical distance through which it falls (effective head, which is the available head minus the losses due to turbulence and friction) according to the following equation [1]

$$E_{hydro} = 2.8 \cdot 10^6 \cdot n_{tr} \cdot n_{HT} \cdot n_{gen} \cdot \rho \cdot 9.81 \cdot h_{eff} \cdot Q \tag{3}$$

where the gravitational acceleration is assumed to be standard (9.81 m/sec^2).

Although it is possible to produce electricity from biomass, it is commonly used to produce heat. This is due to complexity of the energy chain from biomass to electricity: the first step includes a chemical process (pyrolysis, gasification, etc.) to transform biomass to a hydrogen-rich mixture, which should be stored, transported and, finally, utilized in order to produce electricity. The technology for such an energy conversion is not mature enough to be commercialized, therefore biomass combustion sounds more attractive in terms of energy production. The amount of heat produced by biomass depends on the chemical energy contained of the biomass, which is represented by the so-called Low Heating Value (LHV). Accordingly, the annual heat produced is given as [2]

$$E_{biomass} = b \cdot LHV \cdot n_{burner} \tag{4}$$

Economical issues

To achieve an interesting project for electricity production by using RES, it is necessary not only to designing a technologically efficient system but also to assure its viability in terms of economy. To that direction, our model incorporates a complete financial analysis module, where the annual and periodical costs and revenues as well as some feasibility indicators are calculated, based on standard financial terminology [3]. To integrate the model, the following assumptions have been applied:

- The initial investment year is year 0;
- The costs and credits are given in year 0 terms, thus the inflation rate (or the escalation rate) is applied from year 1 onwards;
- The timing of cash flows occurs at the end of the year.

For a reliable calculation of the project's feasibility indicators, a thorough financial analysis is required, which should be consisted of cost and revenue analysis. Due to space limitations, we present only the basic cost parameters for all type of RES, being as follows:

1. Initial Costs (Feasibility study, Development, Engineering, Energy equipment, Balance of equipment, Miscellaneous)
2. Annual Costs (Operation & Management)
3. Periodic Costs (Maintenance & Replacements)

The revenues could be calculated by taking into account the Net Book Value (NBV) of the investment at the end of project life (y) as well as the annual sales of electrical power, given as

$$R_j = c_j \cdot E_j \tag{5}$$

In order to determine the economic effectiveness and feasibility of the project, we calculate the most significant financial indicators. Based on the above analysis, we focus on the Net Present Value (NPV), given as

$$NPV = \sum_{j=1}^{y-1} \frac{F_j}{(1+i)^j} + \frac{F_y + NBV}{(1+i)^y} - IC \quad (6)$$

Furthermore, the Internal Rate of Return (IRR) is also important for the feasibility of the project, being determined as

$$\sum_{j=1}^{y-1} \frac{F_j}{(1+IRR)^j} + \frac{F_y + NBV}{(1+IRR)^y} = IC \quad (7)$$

It is rather evident that a positive value for NPV and an IRR greater than the current discount rate indicates a profitable project.

Modeling

In order to benefit from clean energy technologies, potential users, decision and policy makers, planners, project financiers, and equipment vendors must be able to quickly and easily assess whether a proposed clean energy technology project makes sense. The following model describes a Decision Support System (DSS) that allows for the minimum investment of time and effort and reveals whether or not a potential clean energy project is sufficiently promising to merit further investigation. The considered DSS should be a useful tool specifically aimed at facilitating pre-feasibility and feasibility analysis of clean energy technologies.

The core of such a system is the scenario-building ability in order to propose an integrated apparatus for electricity production by using RES. More precisely, the system should use solar-, wind- and hydro-energy as raw energy resources to produce electricity. The flowchart of such a scenario-building procedure is as follows

1. Selection of the area of interest
2. Presentation of general and energy-related data for the selected region
   - 2.1. Demographical data
   - 2.2. Geographical data
   - 2.3. Climate-related data
   - 2.4. Profile of energy production
   - 2.5. Profile of energy demands
   - 2.6. Presentation of the energy transfer network
3. Presentation of RES potential for the selected region
   - 3.1. Biomass potential in terms of LHV
   - 3.2. Wind energy potential in terms of mean wind speed
   - 3.3. Solar potential in terms of mean annual solar radiation
   - 3.4. Hydropower potential in terms of volumetric flow rate
4. Estimation of RES suitability for the specific area in a [0-10] scale
5. Building the scenario for electricity production
   - 5.1. Project name
   - 5.2. Project location
   - 5.3. RES type selection
   - 5.4. Climate-related data
   - 5.5. Energetic model
   - 5.6. Cost Analysis
   - 5.7. Revenue Analysis
   - 5.8. Feasibility Indicators
6. Presentation of relative case-studies

It is necessary to clarify the suitability estimation mentioned above. For each specific RES, one variable has been determined as critical parameter. More precisely, annual solar radiation has been selected for solar energy, wind speed at 30m height for wind energy, volumetric flow rate for hydroelectricity and Low Heating Value for Biomass. The mean annual value of each of them, normalized over its minimum value allowable for energy production (energy threshold), indicates the suitability index.

Results and Discussion

To underline the effectiveness of the above-mentioned model, a specific case study is studied. The virtual area of interest is assumed to be of high solar radiation, of sufficient wind potential and without any water flow throughout it. For the sake of simplicity, the heat production by biomass is neglected in our calculations, since the potential investor is assumed to be interested only in electricity.

The main objective of this section is to identify the relation between the suitability factor (i.e. the intensity of the available energy potential) and the plants' efficiency in terms of energy and costs. More precisely, we would like to underline that the lower the suitability factor of a specific RES, the lower the technological and economical efficiency for the production of electrical energy using this RES. To prove that allegation, we examine two alternative energy scenarios, where the production of electricity comes from the exploitation of wind and solar energy. We assume that the same amount of electrical energy is produced by both scenarios, in order to have a common bottom line, so as to financially compare the use of wind and solar energy in the specific area, i.e. for given suitability for each RES.

The assumptions for the specific case studies are summarized as follows:

I. The area of interest is approximately 900 m^2, being sufficient for the installation of the main RES conversion systems along with the necessary support facilities.
II. The location of the project is in Athens Greece. (Latitude of project location is 38^0). Thus, the wind energy and solar potential as well as all other necessary weather data were provided by Athens Observatory (Latitude: 37.97^0, Longitude: 23.72^0).
III. The cost analysis is demonstrative and is based on real published RES projects. It is evident that a market research is necessary for an actual project, so as to adequately determine the cost parameters.
IV. There are no legal barriers.
V. The annual electrical energy production for both the wind and solar scenario is decided to be of medium size (about 135 MWh per year).
VI. The technological equipment used in both wind and solar projects is of high quality and efficiency, so as to maximize the utilization of wind and solar potential.
VII. The slope of PV array is set at 300, for optimal underpinning and the orientation factor is set at 0.96

The scenario for production of electricity by using wind and solar energy evolves as follows

1st Step: Determination of the available wind energy and solar potential of the selected region. The mean annual value for the wind speed is U = 5.3 m/sec at 30.5 m height, while the solar radiation is G = 4.32 MWh/m^2.

2nd Step: Determination of suitability for each RES. The solar suitability is found to be 10/10 while the respective suitability for wind power is 5.3/10. Therefore, the most suitable RES for producing electricity is solar energy, in this case.

3rd Step: Calculation of electricity produced. The devices and the technological data used as well as the electrical energy production from wind and solar energy are summarized in the Table 1.

4th Step: Financial analysis and estimation of feasibility indicators. The economical data selected as well as the calculated financial indicators for the above-mentioned cases, are summarized in the Table 2.

Table 1 - Electricity produced

	SOLAR	**WIND**
Device used	Canadian Solar-CS6B/160M	Bergey Windpower, model BERGEY BWC EXCEL 30.5 m Hub Height
Data used	n_{pv}=14.9 %, A_{pv}=1.19 m^2, OR=0.96, G=4.32 MWh/m^2, n_{inv}=90 %, K_{pv}=204	n_{conv}=90 %, A_{wt}=39 m^2, U=5.3 m/sec, P=0.381 MWh/m^2, K_{wt}=10
Energy produced	135.008 MWh	133.731 MWh

Table 2 - Financial analysis and Feasibility indicators

Common data	y=30 years, C_j=450 €/MWh, escalation rate of C_j=3 %, inflation rate=2.5 %, discount rate=9 %, debt ratio=60 %, debt interest=4 %, debt term=25 years	
	SOLAR	**WIND**
	Initial costs	
feasibility study	10,670 €	10,670 €
development	16,510 €	16,510 €
engineering	57,045 €	610,500 €
energy equipment	469,200 €	433,000 €
balance	249,165 € (equipment)	2,613,000 € (plant)
miscellaneous	40,539€	40,539 €
Subtotal:	**843,129 €**	**3,724,309 €**
Annual costs	880 €	92,027 €
Periodic costs for 12 years	20,000 €	200,000 €
annual revenues	60,937 €	60,490 €.
Pre-tax IRR	12.9 %	negative
NPV	173,566 €.	-3,409,862 €.

For the case considered, it is rather evident that the investment in solar energy is considerably more profitable than in wind energy, mainly because of the higher suitability of solar energy (10/10 to 5.3/10). Additionally, we can observe that the potential investor must spend significantly more money to produce the same amount of electrical energy in the selected region if he chooses to use the less suitable RES, i.e. wind energy. The discrepancy on the wind-power costs is a built-in deficiency of this RES type, mainly because of the extremely high costs for the plant balance. This barrier could be partially diminished by significantly increasing the electrical power produced where the usage of wind energy would be more attractive.

Nomenclature

A	Surface (Area), m^2
b	Mass of biomass, kg
C	Selling price of each MWh produced, €/MWh
E	Energy, MWh
F	Annual Cash flow, €

G	Mean annual solar radiation, MWh/m^2
h	Effective head, m
I	Discount rate %
IC	Initial costs, €
IRR	Internal rate of return,%
K	Number of devices, -
LHV	Low Heating Value, MWh/kg
n	Efficiency coefficient, %
NBV	Net book value, €
NPV	Net present value, €
OR	Orientation factor, -
ED	Wind energy density, MWh/m^2
P	Electrical power, MW
Q	Volumetric flow rate, m^3/sec
R	Revenue, €
U	Wind speed, m/sec
Y	Expected project life, yr
Greek Symbols	
ρ	Mass density, kg/m^3
Subscripts	
biomass	Energy by biomass
burner	Burner
conv	AC/DC or DC/AC converter
eff	Effective
gen	Generator
HT	Hydro Turbine
inv	Inverter
j	Year Indicator
y	Project Life
PV	Photovoltaic
solar	Solar energy
tr	Transfer Box
wind	Wind energy
WT	Wind Turbine

Conclusions

A tool for benchmarking of several types of RES, in terms of technological and economical efficiency, is presented here. The corresponding mathematical model allows the creation of several scenarios for electricity production, based on the use of different RES. Each scenario is ranked in terms of energy efficiency and economical viability. As a result, the model could be very useful for potential investors in the area of RES based electricity production.

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