

Watson, Daren; Binnie, Yekini; Duncan, Keith; Dorville, Jean-Francois

Article

Photurgen: The open source software for the analysis and design of hybrid solar wind energy systems in the Caribbean region: a brief introduction to its development policy

Energy Reports

Provided in Cooperation with:

Elsevier

Suggested Citation: Watson, Daren; Binnie, Yekini; Duncan, Keith; Dorville, Jean-Francois (2017) : Photurgen: The open source software for the analysis and design of hybrid solar wind energy systems in the Caribbean region: a brief introduction to its development policy, Energy Reports, ISSN 2352-4847, Elsevier, Amsterdam, Vol. 3, pp. 61-69, <https://doi.org/10.1016/j.egy.2017.03.001>

This Version is available at:

<https://hdl.handle.net/10419/187868>

Standard-Nutzungsbedingungen:

Die Dokumente auf EconStor dürfen zu eigenen wissenschaftlichen Zwecken und zum Privatgebrauch gespeichert und kopiert werden.

Sie dürfen die Dokumente nicht für öffentliche oder kommerzielle Zwecke vervielfältigen, öffentlich ausstellen, öffentlich zugänglich machen, vertreiben oder anderweitig nutzen.

Sofern die Verfasser die Dokumente unter Open-Content-Lizenzen (insbesondere CC-Lizenzen) zur Verfügung gestellt haben sollten, gelten abweichend von diesen Nutzungsbedingungen die in der dort genannten Lizenz gewährten Nutzungsrechte.

Terms of use:

Documents in EconStor may be saved and copied for your personal and scholarly purposes.

You are not to copy documents for public or commercial purposes, to exhibit the documents publicly, to make them publicly available on the internet, or to distribute or otherwise use the documents in public.

If the documents have been made available under an Open Content Licence (especially Creative Commons Licences), you may exercise further usage rights as specified in the indicated licence.



<https://creativecommons.org/licenses/by-nc-nd/4.0/>



Photurgen: The open source software for the analysis and design of hybrid solar wind energy systems in the Caribbean region: A brief introduction to its development policy



Daren Watson^{a,*}, Yekini Binnie^a, Keith Duncan^b, Jean-Francois Dorville^c

^a University of the West Indies, Kingston, Jamaica

^b Southeastern University, FL, United States

^c Météo-France, Martinique

ARTICLE INFO

Article history:

Received 3 October 2016

Received in revised form

10 March 2017

Accepted 21 March 2017

Available online 18 April 2017

Keywords:

Caribbean

Modelling tool

Optimization

Renewable energy

Solar

Wind

ABSTRACT

Hybrid Renewable Energy Systems (HRES) use multiple renewable resources such as hydro, solar and wind collaboratively to produce energy that can meet a defined load demand continuously. Their combination can lead to the improvement in the systems efficiency and overall reliability. However, the level of penetration of HRES in the Caribbean region is less than its expected potential. The constraints generated by their complexity and the costly access to useful energy planning tools is a limitation to their implementation. Therefore, in collaboration with the Alternative Energy Research Group, UWI Mona, we develop a free Linear Optimization software, Photurgen, for the design and analysis of hybrid solar-wind systems within the Caribbean region. Solar-wind hybrid systems are simulated based on historic climatological resources and instantaneous load consumption data, providing the user with graphics and advice for their optimal configuration. This paper introduces the first version of Photurgen and its associated development policies. This tool is one simple solution to be applied to increase the rate of autonomous and grid-tied households within the region, with Jamaica being its experimental location.

© 2017 The Authors. Published by Elsevier Ltd.

This is an open access article under the CC BY-NC-ND license (<http://creativecommons.org/licenses/by-nc-nd/4.0/>).

1. Introduction

Hybrid Renewable Energy Systems (HRES) which is schematized in the diagram of Fig. 1 use a combination of renewable sources to produce energy that can meet a defined load demand continuously. The renewable source can be varied in terms of nature and efficiency such as biomass, hydro, solar and wind in conjunction with a backup system (i.e.; generator, battery pack). Their combination leads to the improvement in the system's efficiency and overall reliability. Renewable energy resources such as solar and wind have shown since the early 2000s, the capacity for sustainable and economically feasible energy production (Abbes et al., 2014; Bilal et al., 2013; Cabral et al., 2010), while warranting the power level. The quality of the resources determines the energy storage needs for stand-alone (i.e. off grid or autonomous) applications as outlined by Zhou et al. (2010). The storage systems include electrochemical batteries, flywheels and hydrogen fuel cells

which intakes excess energy produced by the generators for use at a later date (Belmili et al., 2013). In Fig. 1, the main energy production is provided by solar panels and a small wind turbine in direct current,¹ stored by a battery bank and delivered to the consumer through an inverter (DC to AC). Energy security of the site is warranted by the minimal level of charge of the battery, a connection to the national grid and/or by a biodiesel fuelled generator. Zhou et al. (2010) further state that there has been an increased utilization of hybrid systems for decentralized power generation and distribution such as for telecommunication stations and residential properties since the oil crisis of the early 1970s. Conventionally, solar and wind are considered to be amongst the most ubiquitous renewable resources for electricity generation in remote areas. Unfortunately, factors such as the break even distance, reduced population size, low income and economic activity (Bawah et al., 2013) as well as a lack of technical capacity contributes to the low penetration of energy systems in these rural areas. Furthermore, coupled with the highly intermittent nature of

* Corresponding author.

E-mail address: daren.watson02@uwimona.edu.jm (D. Watson).

¹ Larger wind turbines (i.e. 1 MW, 2 MW etc.) produces AC power.

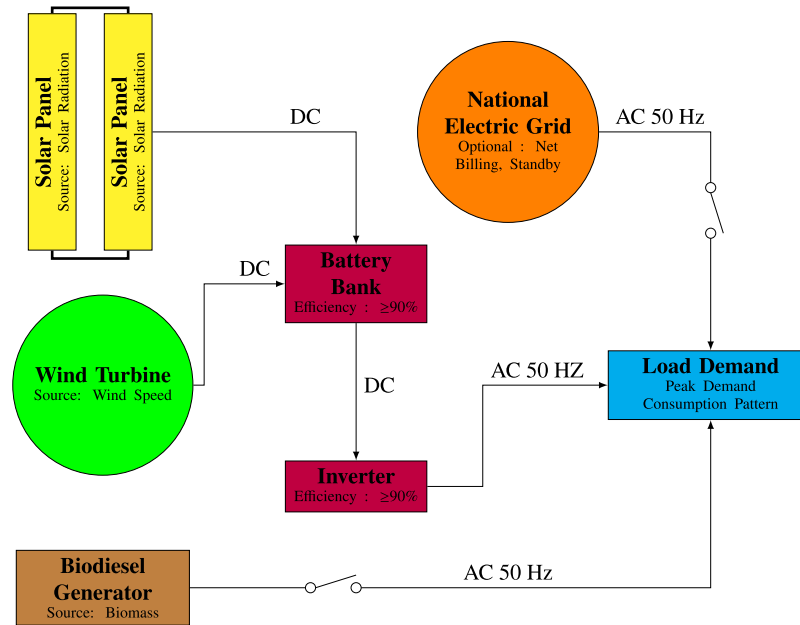


Fig. 1. Schematic of a Hybrid Renewable Energy System (HRES).

Table 1

Non exhaustive list of renewable energy system modelling software.

| Energy tool | Training required | Availability | Year of release |
|-------------|-------------------|---------------|-----------------|
| EMPS | 1 Month | Proprietary | 1975 |
| LEAP | 4 Days | Proprietary | 1980 |
| HOMER | 1 Day | Proprietary | 1992 |
| NEMS | User Specific | Free Download | 1993 |
| PRODRISK | 1 Week | Proprietary | 1994 |
| GTMAZ | 1 Week | Proprietary | 1995 |
| ENERGYPLAN | 1 Month | Free Download | 1999 |
| BALMOREL | 1 Week | Open-Source | 2000 |
| EMCAS | 2 Weeks | Proprietary | 2002 |
| BCHP | 1 Week | Free Download | 2003 |
| WILMAR | 3 Months | Proprietary | 2006 |
| COMPOSE | 3 Days | Free Download | 2008 |

wind and solar regimes, hybrid energy systems have proven to be rather complex in their analysis given the non-linear properties of components, vast amount of variables and parameters to consider and the interdependence of both the optimum configuration and the optimization technique (Zhou et al., 2010). Hence, it is impossible to model safe energy systems without the aid of computational software (Connolly et al., 2010).

Many energy planning tools are created for system modelling. Table 1 presents a truncated list, each with its own applications for a defined context. Connolly et al. (2010) highlight the application of over fifty different energy tools used in energy management. Most of these software are European based (i.e.; temperate climate and industrialized areas); conceptualized and developed in research institutions with a high level of expert human resource (Urban et al., 2007). Bialasiewicz and Muljadi (2006) in conjunction with the National Renewable Energy Laboratory (NREL) develop the RPM Simulator to conduct feasibility assessment of wind-solar-diesel hybrid power systems. The Integrated Markal-Efom System (TIMES) looks at temporally and spatially disaggregated problems in energy systems with focus on GIS modelling (Henggeler Antunes et al., 2008). An open source tool is created by Howells et al. (2011) for the sizing of energy systems. This tool is later improved by Welsch et al. (2012) to facilitate the modelling of elements of smart grids. Cormio et al. (2003) apply a Linear Programming (LP) based tool known as the Energy Flow Optimization Model (EFOM) to the Apulia region in southern Italy to assess the possible

reduction in environmental impacts and economic efforts by applying combined heat and power systems. Another LP model, the MARKAL, created by the International Energy Agency (IEA) in 2001 takes a bottom up approach in finding the least cost solution given economic constraints (Zonooz et al., 2009). These tools developed since the last 30 years try to tackle the need of mastering energy production and consumption using recent technology (i.e. smart grid, GIS, data mining, etc.)

Notwithstanding the changes in technology and the development of optimization tools for energy planning, it is important that the knowledge and technical capacity of the local consumers and producers of energy be increased to accommodate the advances within this sector. The Caribbean, mainly consisting of developing territories, for the most part non interconnected islands, has a large reliance on fossil fuels for energy generation. A progressive push to lessen the dependence on oil and reduce its inevitable economic burden has lead to the steady adoption of renewable energy technologies (Headley, 1997; Haraksingh, 2001; McDonald, 2012). Nonetheless, there exist a fundamental gap in the human capacity of the region as it relates to the optimization and design of renewable energy systems, particularly for solar and wind power. This is mainly driven by the limitations of existing tools required for these capabilities, namely, inaccessibility due to the requirements of a license, non-flexibility for case specific analyses, and the lack of regional research and development on energy matters. According to Jebaraj and Iniyar (2006), software is a standard necessity in en-

ergy planning. Hence considerable efforts must be made to formulate and have them implemented for energy planning strategies.

Urban et al. (2007) in their study justify the necessity for the research conducted in this paper. They focus on the characteristics of developing regions, particularly within Asia and highlight the gaps in the existing energy planning tools when considering such locations. To solve this problem, Urban et al. (2007) suggest the development of new models or an improvement in the already existing ones to sufficiently account for the characteristics of the developing countries' energy systems and economies.

1.1. Objectives of study

Consider the application of an open source software of computations, Photurgen² that can determine the most suitable capacity of solar-wind system to be installed at locations within the Caribbean region (i.e.; tropical insular areas of developing countries with high solar radiation rate and a continuous wind regime). This numerical tool is both quantitative and qualitative in its output, focusing on system design and optimization. This is an initial step in providing platforms by which human capacity within the region can increase in alternative energy. The development of Photurgen, seeks to address the lack of regionally intrinsic tools which are free for use, open for collaborations amongst regional experts and effective for energy planning involving solar-wind systems. The paper is outlined as follows. Section 2 details the development policy of the tool with Sections 2.1–2.3 highlighting the various functionalities currently available. Conclusions are gathered in Section 3.

2. Development policy

The Python 2.7 programming language is used for the development of Photurgen due to its wide accessibility and high level understanding when compared to other languages. The Linux OS is also the current platform for the authors. Python built-in libraries such as numpy, matplotlib and scipy are supplemented with the authors' own libraries to form computational scripts for each of the functionality (see Sections 2.1–2.3) of the tool.

Photurgen is a data-driven, open source, numerical tool used for the optimization of hybrid solar-wind systems. According to Watson (2016), HRES requires at least one year of climatological and load consumption data from the proposed installation site. Using a combination of modules and sub-modules (computational code), the end user is able to empirically determine the optimal mix of solar panels and wind turbines applicable to the specific locations. Currently, only locations on the island of Jamaica (see Fig. 3) are accessible. This limitation only exists due to the authors' use of Jamaica as the experimental location for the tool. Additional Caribbean territories will be added in keeping with the regional expansion of the software.

The tool is accessible in two forms; Command Line Interface (CLI) and Graphical User Interface (GUI) (see Fig. 3). Both versions are only compatible with the Linux Operating System. The former version seeks to attract contributors for its continued development, while the latter is for regular application by the public. The developers are also working on a Windows compatible version for release in 2017. Notwithstanding, both versions are freely accessible and can be obtained if requested from the software's website.³ The tool has three (3) main modules as shown in Fig. 2; Photurgen Analysis (PTGA) for data analysis; Photurgen Optimization (PTGO) for system design; and Photurgen Geographic Information System (PTGGIS) for map viewing.

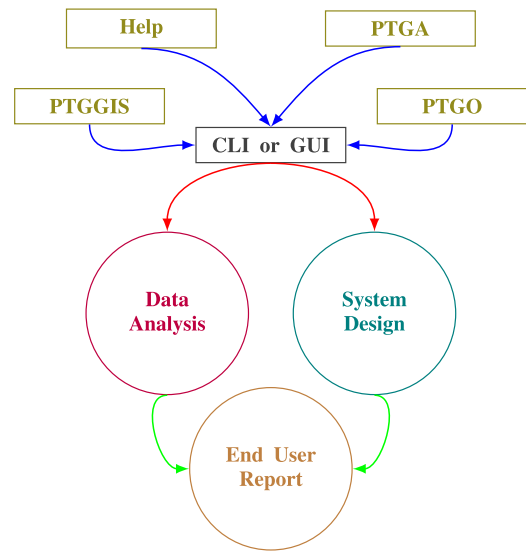


Fig. 2. Developer schematic of the Photurgen energy planning software.

2.1. Photurgen analysis (PTGA)

The application of solar-wind systems can be complex, due to the high variability of the natural resources that governs their application (Abbes et al., 2014). Solar is a diurnal resource, highly dependent on the cloud cover and the concentration of particles in the air. Often times, this is ignored, with systems being sized based solely on the load demand. Hence, consumers are left with under performing installations, resulting in dissatisfaction and a negative outlook on non-conventional energy production. PTGA is an autonomous module designed to conduct essential analyses of weather parameters at a given location i.e. data collected from a potential HRES location or historical data of a data base. The ability to simulate individual mathematical models of solar modules and wind turbines or use them simultaneously makes PTGA a comprehensive analytical tool.

2.1.1. Renewable resource assessment

This functionality uses time series of weather parameters, including; air density; air pressure; ambient temperature; cooling degree days; dew point temperature; equilibrium moisture content; evapo-transpiration; humidity; rain rate; solar energy; solar radiation; uv index; wind chill; wind direction; wind run; and wind speed to give the end user graphical representations of the persistent weather patterns at the location of study. However, only air pressure, ambient temperature, solar radiation and wind speed are used by PTGA for assessing the expected performance of solar panels and wind turbines at the selected location. The simple power law (Amarakoon and Chen, 2001; Watson, 2016) is also incorporated in this simulation for the conversion of wind data to the industrial standard of 15 m.

$$v(t) = v_{h_{ref}}(t) * \left(\frac{h_{hub}}{h_{ref}} \right)^{\alpha} \quad \text{for } t = 1, \dots, n \quad (1)$$

where $\alpha = 1/7$ in stable environments,⁴ $v_{h_{ref}}$ is the wind speed at the measured/reference height, h_{ref} is the reference height and h_{hub} is the hub height of the wind turbine. Fig. 4 depicts the polar wind rose of the measured data.

² Pronounced as "fo-ter-gen". Pho—photovoltaics, tur—turbines, gen—generators.

³ Visit www.photurgen.com for more information.

⁴ Provided no anomalous atmospheric activity occurred during data collection.

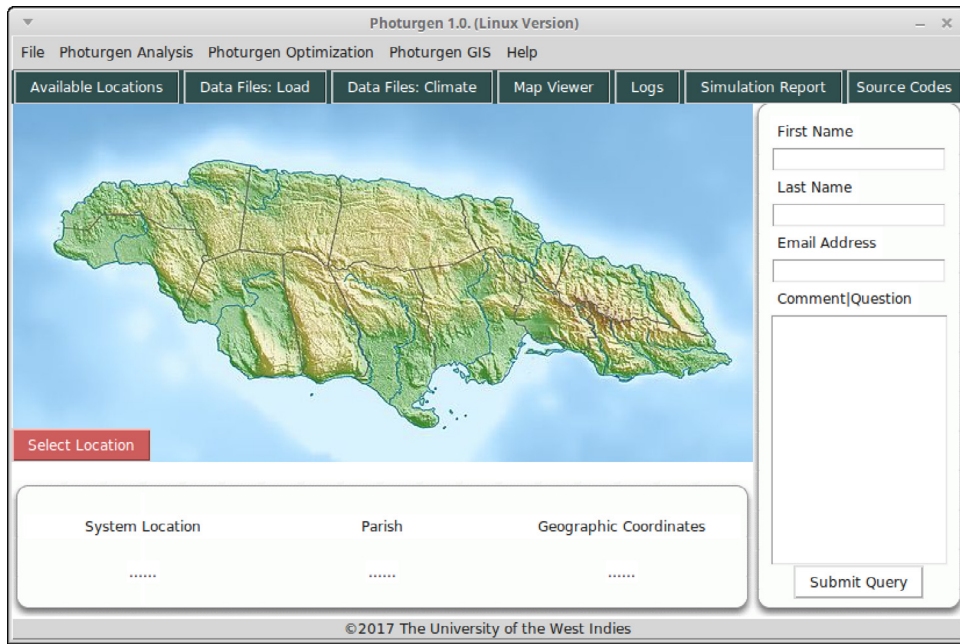


Fig. 3. General user interface of Photurgen.

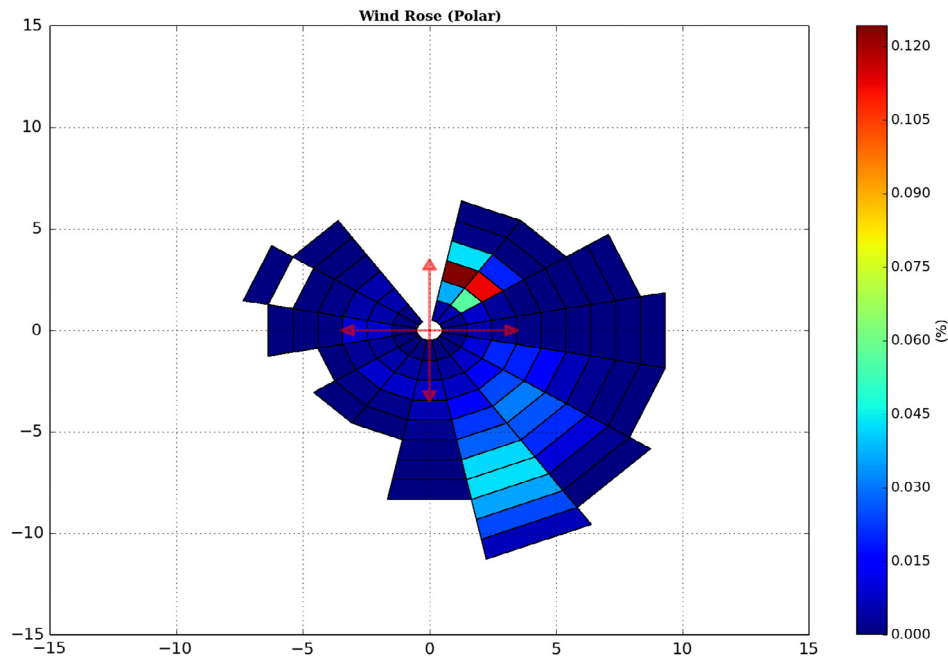


Fig. 4. Wind rose of measured wind speeds.

2.1.2. Load consumption analysis

Electrical data obtained from the location of interest is analysed on a daily (see Fig. 5), weekly and monthly (i.e. if one year of data is obtained) scale. Using the utility's cost of energy, the associated purchases made from the grid are calculated. Furthermore, the peak load demand is determined and stored for later use by the optimization modules.

2.1.3. Energy system performance

Key inputs for the performance analysis of solar modules are the module specifications and time series of temperature and solar radiation. Power production of the modules are calculated using

Eq. (2) (Watson, 2016).

$$P_{pv}(t) = \left(I_{ph}(t) - I_0(t) \left(\exp \left(\frac{q(V_{oc}(t) + I_{pv}(t) * R_s)}{A * K * T(t)} \right) - 1 \right) - \frac{V_{oc}(t)}{R_{sh}} \right) V_{pv}(t) \quad \text{for } t = 1, \dots, n \quad (2)$$

where I_{ph} is the illumination current, I_0 is the reverse saturation current, q is the charge of an electron, V_{oc} is the open circuit voltage, V_{pv} is the operating voltage, A is the ideality factor, K is the Boltzmann constant, R_s is the series resistance, R_{sh} is the shunt resistance, and T is the temperature of the cell.

Similarly, key inputs for the performance analysis of wind turbines are the turbine specifications and time series of air

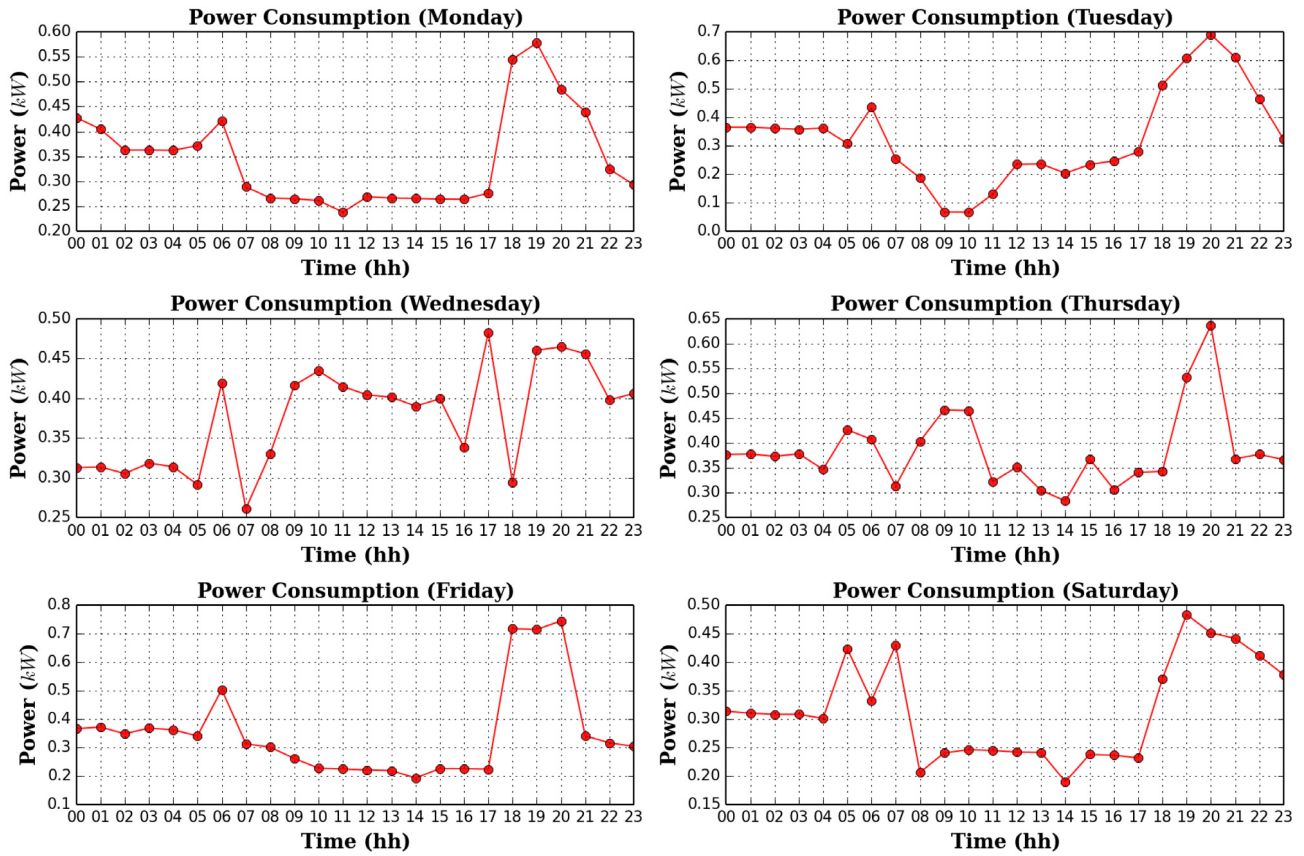


Fig. 5. Daily analysis of measured load consumption.

density, temperature and wind speeds. Power production of the wind turbine is calculated using the following equation (Watson, 2016)

$$P_{wind}(t) = \begin{cases} av(t)^3 - bP_r & \text{if } v_{cin} \leq v(t) < v_r \\ P_r & \text{if } v_r \leq v(t) < v_{cout} \\ 0 & \text{otherwise} \end{cases} \quad (3)$$

where,

$$a = \frac{P_r}{v_r^3 - v_{cin}^3} \quad (4)$$

and

$$b = \frac{v_{cin}^3}{v_r^3 - v_{cin}^3} \quad (5)$$

where P_r is the rated power produced by the turbine, v_{cin} is the cut-in wind speed, v_{cout} is the cut-out wind speed and v_r is the rated wind speed of the wind turbine. **a** and **b** are turbine specific coefficients.

2.1.4. Auto-regressive integrated moving average

The prediction of future data (unknown series) from past values (known series) is of importance for energy system monitoring, evaluation and operation, especially in the case of grid-tied facilities (Daniel and Chen, 1991). There exists a number of techniques for the forecasting of data, namely, Numerical Weather Prediction, Regression Analysis, Neural Networks and Time-Series Analysis (Cococcioni et al., 2011). Boone (2005) states that time-series models are the simplest to determine the trend in the data. This trend allows for extrapolation of the data for future values. Moreover, for short term predictions, time-series models

such as the Auto-Regressive Integrated Moving Average (hereafter denoted as ARIMA(p, d, q)) is most accurate (Boone, 2005). Katz and Skaggs (1981) further state that their applications to climatological sequences are prevalent. Since power production is derived from solar radiation in the case of photovoltaic modules and wind speed in the case of wind turbines, forecasting of both variables can also be used to predict the short term power output of these components (Daniel and Chen, 1991). The same is applicable to the load consumption.

An ARIMA(p, d, q) simulation is incorporated into the software. The terms p and q are the orders of the Autoregressive and Moving Average models respectively and d is the degree of differencing required to make the data stationary (Box and Jenkins, 1976). This functionality enables the end user to predict future data or extend a previously acquired time series (i.e. both climatological and electrical time series). Autocorrelation Functions (ACF) and Partial Autocorrelation Functions (PACF) are obtained from the datasets which then provides the insight for the selection of the most accurate order of the ARIMA(p, d, q) model for forecasting (Watson, 2016).

An exponential decrease of the ACF coupled with a spike of the PACF in the initial lags would suggest an autoregressive process being most ideal. On the other hand, an exponential decrease of the PACF coupled with a spike of the ACF in the initial lags would suggest a moving average process. However, if both the ACF and PACF decline slowly, then a mixed process is suggested. This mode of determining p and q nonetheless is more intuitive (i.e. graphical) than empirical and is mostly used in the initial phase of order determination.

2.2. Photurgen optimization (PTGO)

Optimization can be described as a selection of the most ideal element from a subset of feasible solutions. In the case

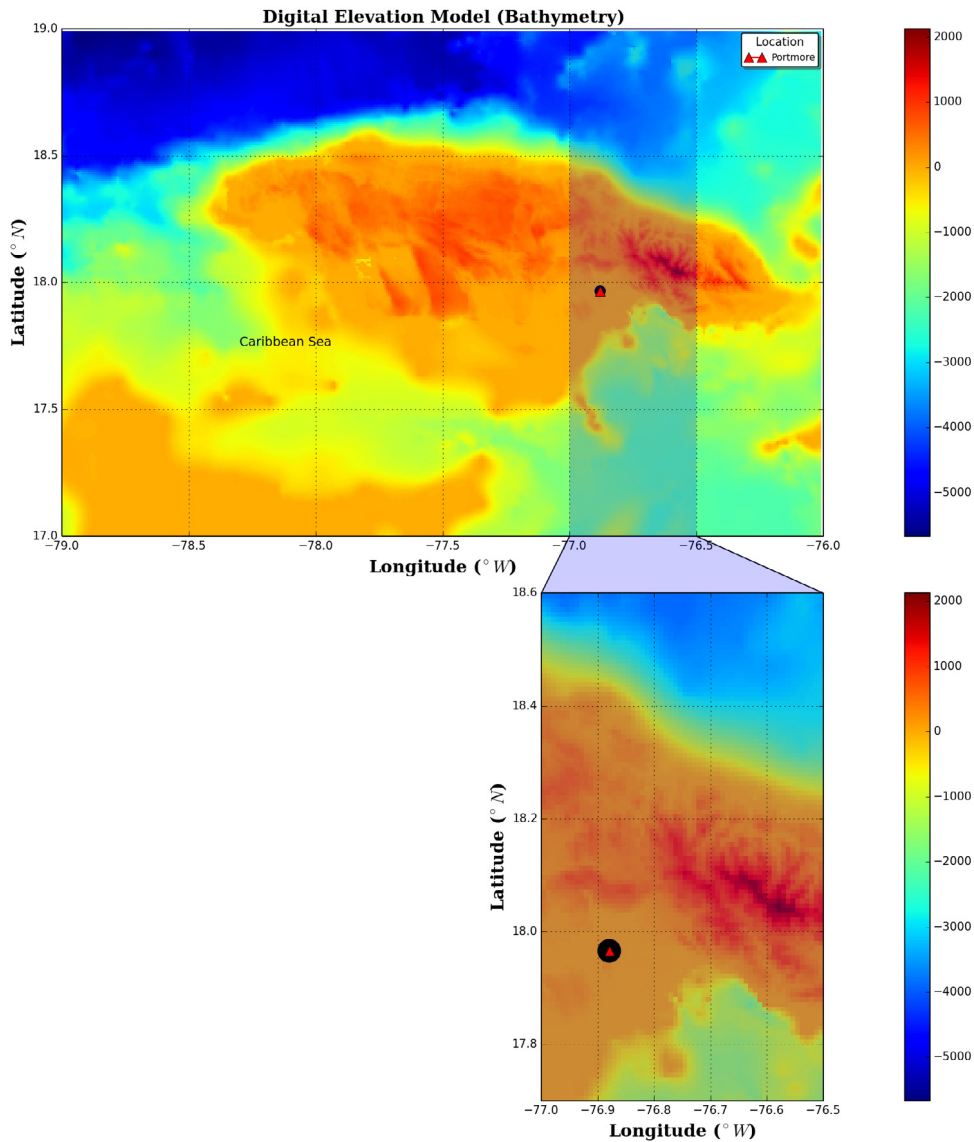


Fig. 6. Bathymetry of Jamaica.

of solar-wind hybrid systems, designers take one of two or both viewpoints. Either systems are optimized to meet technical requirements such as the capacity factor and peak energy demand or economic requirements such as the Levelized Cost of Energy (LCOE) and capital cost of the system. When both sets of requirements are taken into account, this is referred to as Techno-Economic Optimization. PTGO uses a Linear Optimization technique (i.e. Iterative Method) for the economic assessment of the renewable energy technologies.

2.2.1. System optimization

An Optimal System Plot, which is a three dimensional representation of the sensitivity analyses is produced by PTGO. Requirements for the simulation of this module include; the lifetime of the project, discount rate, capital cost, fixed operation and maintenance cost, variable operation and maintenance cost and the number of solar modules/wind turbines. Most essential to PTGO is the ability to identify the best combination of renewable energy technology. Sensitivity analyses of all possible combinations are simulated, with the most feasible solution being constrained by an optimization metric such as the LCOE. The

Levelized Cost Of Energy is calculated using Eq. (6) (Patel, 2006).

$$LCOE = \frac{(((\%_{wind} * c_{wind}) + (\%_{solar} * c_{solar})) * CRF) + (FOM_{wind} + FOM_{solar})}{8760 * cap_{factor}} + (VOM_{wind} + VOM_{solar}) * E_T \quad (6)$$

where $\%_{solar}$ and $\%_{wind}$ are the percentage of solar and wind penetration respectively, relative to the total number of units. c_{solar} and c_{wind} are the system costs per unit capacity (\$/kW) for residential solar and wind systems respectively, according to market conditions. FOM_{solar} , VOM_{solar} , FOM_{wind} and VOM_{wind} are the fixed and variable operation and maintenance cost of the respective systems. E_T is the annual energy production of the system. CRF is the capital recovery factor of the project (see Eq. (7)) (Patel, 2006).

$$CRF = \frac{i(1+i)^n}{(1+i)^n - 1} \quad (7)$$

where i is the interest rate and n , the number of annuities received.

2.3. Photurgen geographical information system (PTGGIS)

Geographic Information Systems (GIS) are important when assessing climatological conditions and topographical features of

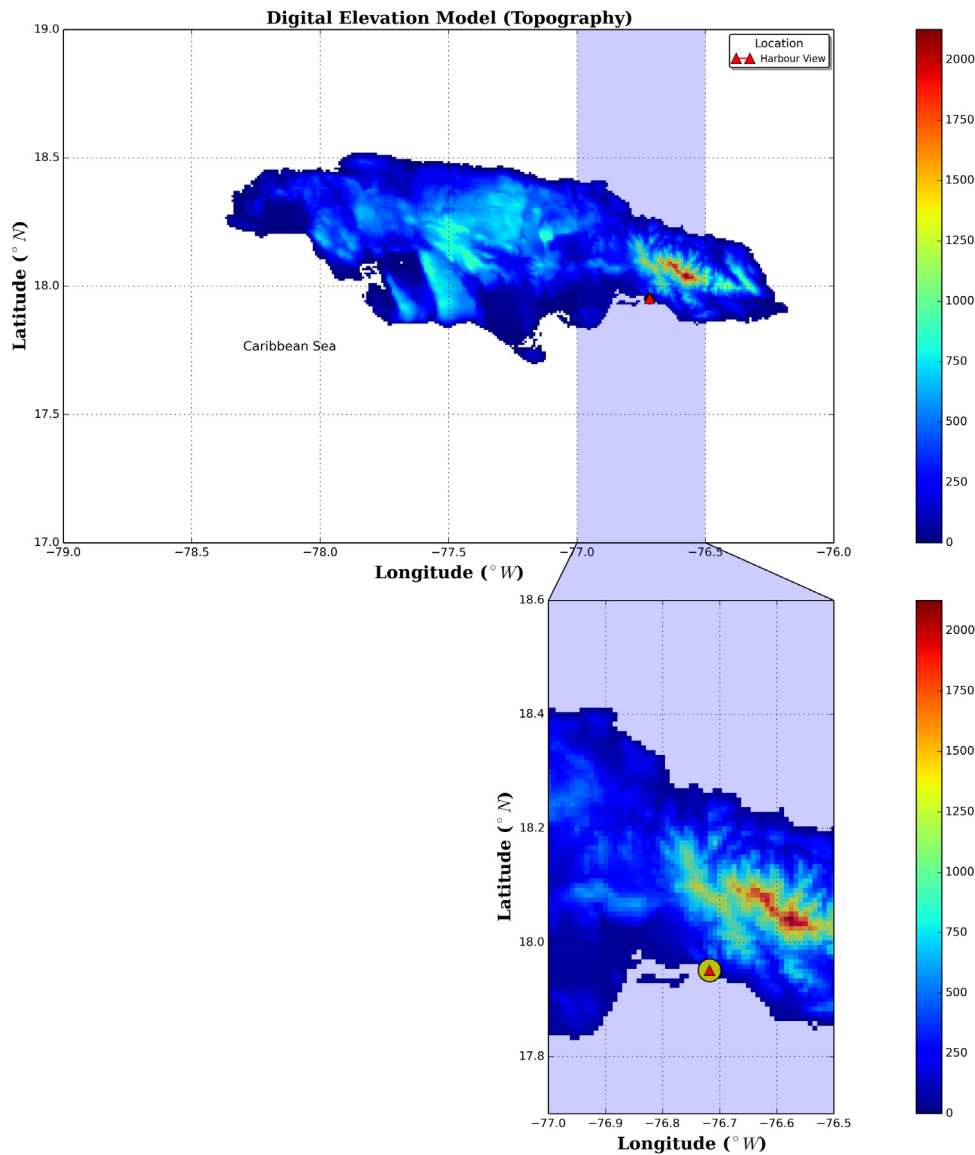


Fig. 7. Digital elevation model of Jamaica.

geographical areas. GIS platforms give the ability to map, model and analyze vast quantities of data within a database consisting of variables matched to coordinates.

PTGGIS is designed to read and modify different GIS file formats for site specific assessment. It also presents the findings of these processes graphically in the form of maps as depicted in Figs. 6 and 7. In Figs. 6 and 7, the experimental location is highlighted and isolated into a sub-plot; showing the referencing capability of the tool. This feature is most convenient when working with resource databases such as wind and solar maps.

It should be noted that PTGGIS will not have the full capabilities of tools such as ArcGIS. The authors' main intention is to provide energy planners with the ability to view resource maps conveniently, streamlining all the processes required for assessment into one simple tool.

2.4. Simulation report

With the developer's push to keep the software as simple as is technically possible, graphical and numerical output of all simulations are automatically compiled and stored as a pdf report. This gives the end user the ease of accessing the required information in a coalesced form (see Fig. 8).

3. Concluding remarks

This paper details the objectives achieved in the development of the Photurgen energy planning tool, its modular structure and functionalities. At the risk of stating the obvious, each module has different capabilities according to their namesake i.e. PTGA deals with data analysis and statistics, PTGO focuses on system economics and optimization while PTGGIS involves geo-referencing. This is one of the possible solutions for increasing human capacity in the energy sector within the Caribbean. Proprietary tools such as Homer Energy have often been applied for the optimization of renewable energy systems on numerous occasions. Nonetheless, there exist limitations such as inaccessibility, financial investments (licensing) among others that have little positive result on the lack of penetration in this region. Photurgen, a data-driven open-source energy planning model will seek to address such limitations while exploiting input from regional experts and academia within the Caribbean.

The main advantage to the open-source community is the continuous scrutiny of the shared source codes. Hence, future research lies in the development of Photurgen and its application to a greater spectrum of energy technologies, than is investigated


|  Optimization Results | | | | | |
|---|--------------|---------------|----------|--------------|--------------|
| Solar Module | Wind Turbine | LCOE (\$/kWh) | NPC (\$) | Capital (\$) | Energy (kWh) |
| 0.0 | 7.0 | 0.64 | 9800.0 | 1400.0 | 3345.97 |
| 1.0 | 6.0 | 0.63 | 10454.79 | 1671.43 | 3331.03 |
| 2.0 | 5.0 | 0.61 | 10705.14 | 1942.86 | 3316.09 |
| 3.0 | 4.0 | 0.58 | 10551.07 | 2214.29 | 3301.15 |
| 4.0 | 3.0 | 0.53 | 9992.57 | 2485.71 | 3286.2 |
| 5.0 | 2.0 | 0.47 | 9029.64 | 2757.14 | 3271.26 |
| 6.0 | 1.0 | 0.39 | 7662.29 | 3028.57 | 3256.32 |

Fig. 8. Results page of PTGO report.

by this paper. Further development will see the enhancement of the input and output capabilities for the end user as well as the refinement of the algorithms used for the computations. The development policy will also facilitate a Windows version to the tool and other Caribbean territories are to be incorporated in future versions. The possibility also exists for greater data acquisition and analysis across Jamaica, our experimental location. This is significant for the classification of climatological resources around the island. A similar approach can also be adopted for other Caribbean territories.

Acknowledgements

The authors would like to acknowledge the Department of Physics at The University of the West Indies for its continued support. We thank our funding partners, Dr. Keith Duncan at the Southeastern University and the Office of the Deputy Principal at the University of the West Indies for the New Initiative Grant (Feasibility Study of Renewable Energy Production in Jamaican Communities⁵). Also, we wish to thank the reviewers for their valuable comments and criticisms.

References

- Abbes, D., Martinez, A., Champenois, G., 2014. Life cycle cost, embodied energy and loss of power supply probability for the optimal design of hybrid power systems. *Math. Comput. Simulation* 98, 46–62. <http://dx.doi.org/10.1016/j.matcom.2013.05.004>.
- Amarakoon, A.M.D., Chen, A.A., 2001. Modelling of wind speed and power across Jamaica. *Jamaican J. Sci. Technol.* 12, 48–64.
- Bawah, U., Addoweesh, K., Eltamaly, A.M., 2013. Comparative study of economic viability of rural electrification using renewable energy resources versus diesel generator option in Saudi Arabia. *J. Renew. Sustain. Energy* 5 (4), 42701–427017. <http://dx.doi.org/10.1063/1.4812646>.
- Belmili, H., Almi, M.F., Bendib, B., Bolouma, S., 2013. A computer program development for sizing stand-alone photovoltaic wind hybrid systems. *Energy Procedia* 36, 546–557. <http://dx.doi.org/10.1016/j.egypro.2013.07.063>.
- Bialasiewicz, J., Muljadi, E., 2006. Analysis of renewable energy systems using RPM-SIM simulator. *IEEE Trans. Ind. Electron.* 53 (4), 1137–1143.
- Bilal, B.O., Sambou, V., Ndiaye, P., Kebe, C., Ndongo, M., 2013. Study of the influence of load profile variation on the optimal sizing of a standalone hybrid PV/wind/battery/diesel system. *Energy Procedia* 36 (2013), 1265–1275. <http://dx.doi.org/10.1016/j.egypro.2013.07.143>.
- Boone, A., 2005. *Simulation of Short-Term Wind Speed Forecast Errors using a Multi-Variate ARMA (1,1) Time Series Model* (Master of Science thesis), Royal Institute of Technology, Stockholm, Sweden.
- Box, G.E., Jenkins, G.M., 1976. *Time Series Analysis: Forecasting and Control*. John Wiley & Sons, Ltd., New Jersey, USA.
- Cabral, C.V.T., Filho, D.O., Diniz, A.S.A.C., Martins, J.H., Toledo, O.M., de Vilhena, L., Machado Neto, B., 2010. A stochastic method for stand-alone photovoltaic system sizing. *Sol. Energy* 84 (9), 1628–1636. <http://dx.doi.org/10.1016/j.solener.2010.06.006>.
- Cococcioni, M., Lazzarini, B., D'Andrea, E., 2011. 24 hour ahead forecasting of energy production in solar PV systems. In: *11th International Conference on Intelligent Systems Design and Applications*. IEEE, Cordoba, Spain, pp. 1276–1281.
- Connolly, D., Lund, H., Mathiesen, B.V., Leahy, M., 2010. A review of computer tools for analysing the integration of renewable energy into various energy systems. *Appl. Energy* 87 (4), 1059–1082. <http://dx.doi.org/10.1016/j.apenergy.2009.09.026>.
- Cormio, C., Dicorato, M., Minola, A., Trovato, M., 2003. A regional energy planning methodology including renewable energy sources and environmental constraints. *Renewable Sustainable Energy Rev.* 7 (2), 99–130.
- Daniel, A., Chen, A.A., 1991. Stochastic simulation and forecasting of hourly average wind speed sequences in Jamaica. *Sol. Energy* 46 (1), 1–11.
- Haraksingh, I., 2001. Renewable energy policy development in the Caribbean. *Renew. Energy* 24 (34), 647–655. [http://dx.doi.org/10.1016/S0960-1481\(01\)00051-9](http://dx.doi.org/10.1016/S0960-1481(01)00051-9).
- Headley, O., 1997. Renewable energy technologies in the Caribbean. *Sol. Energy* 59, 1–9.
- Henggeler Antunes, C., Gomes, A., Biberacher, M., 2008. GIS based modeling approach for energy systems. *Int. J. Energy Sect. Manage.* 2 (3), 368–384.
- Howells, M., Rogner, H., Strachan, N., Heaps, C., Huntington, H., Kypros, S., Hughes, A., Silveira, S., DeCarolis, J., Bazillian, M., Roehrl, A., 2011. OSEMOSSYS: The open source energy modeling system: An introduction to its ethos, structure and development. *Energy Policy* 39 (10), 5850–5870. <http://dx.doi.org/10.1016/j.enpol.2011.06.033>.
- Jebbaraj, S., Iniyar, S., 2006. A review of energy models. *Renewable Sustainable Energy Rev.* 10 (4), 281–311.
- Katz, R., Skaggs, R., 1981. On the use of autoregressive moving average processes to model meteorological time series. *Amer. Meteor. Soc.* 109 (3), 479–484.
- McDonald, P., 2012. Latin America and the Caribbean: Is production approaching its peak? *Oil Energy Trends* 37 (8), 11–19. <http://dx.doi.org/10.1111/j.1744-7992.2012.00238.x>.
- Patel, M.R., 2006. *Wind and Solar Power Systems*, second ed. CRC Press, Florida, USA.
- Urban, F., Benders, R., Moll, H., 2007. Modelling energy systems for developing countries. *Energy Policy* 35 (6), 3473–3482. <http://dx.doi.org/10.1016/j.enpol.2006.12.025>.

⁵ See www.photurgen.com/publications for full report.

- Watson, D., 2016. Realization of an Open Source Software of Computations for the Optimization of Hybrid Renewable Energy Systems: Application in the Caribbean Region (Master of Philosophy thesis), University of the West Indies, Kingston, Jamaica.
- Welsch, M., Howells, M., Bazilian, M., DeCarolis, J., Hermann, S., Rogner, H., 2012. Modelling elements of smart grids: Enhancing the OSeMOSYS (open source energy modelling system) code. *Energy* 46 (1), 337–350.
- Zhou, W., Lou, C., Li, Z., Lu, L., Yang, H., 2010. Current status of research on optimum sizing of standalone hybrid solar wind power generation systems. *Appl. Energy* 87 (2), 380–389. <http://dx.doi.org/10.1016/j.apenergy.2009.08.012>.
- Zonooz, M.R.F., Nophiah, Z., Yosuf, A.M., Sopian, K., 2009. A review of MARKAL energy modeling. *Eur. J. Sci. Res.* 26 (3), 352–361.