OptiCE User Manual

Authors: Dr. Pietro Elia Campana,

M.Sc. Yang Zhang

20th August 2017

Table of Contents

1 Introduction

OptiCE is an open source code for simulation, optimization, and design of hybrid power systems for off-grid and on-grid applications [1]. OptiCE models clean energy technologies integrated in microgrids or as distributed generation in larger grids. The model is written in Matlab® language and uses genetic algorithms to find the best power sources, storage system, and back-up sources combination to minimize life cycle cost and maximize renewable power system reliability. It covers the whole chain of energy systems including mainly 6 areas, i.e., renewable energy, conversion technologies, mitigation technologies, intelligent energy uses, energy storage and sustainability.

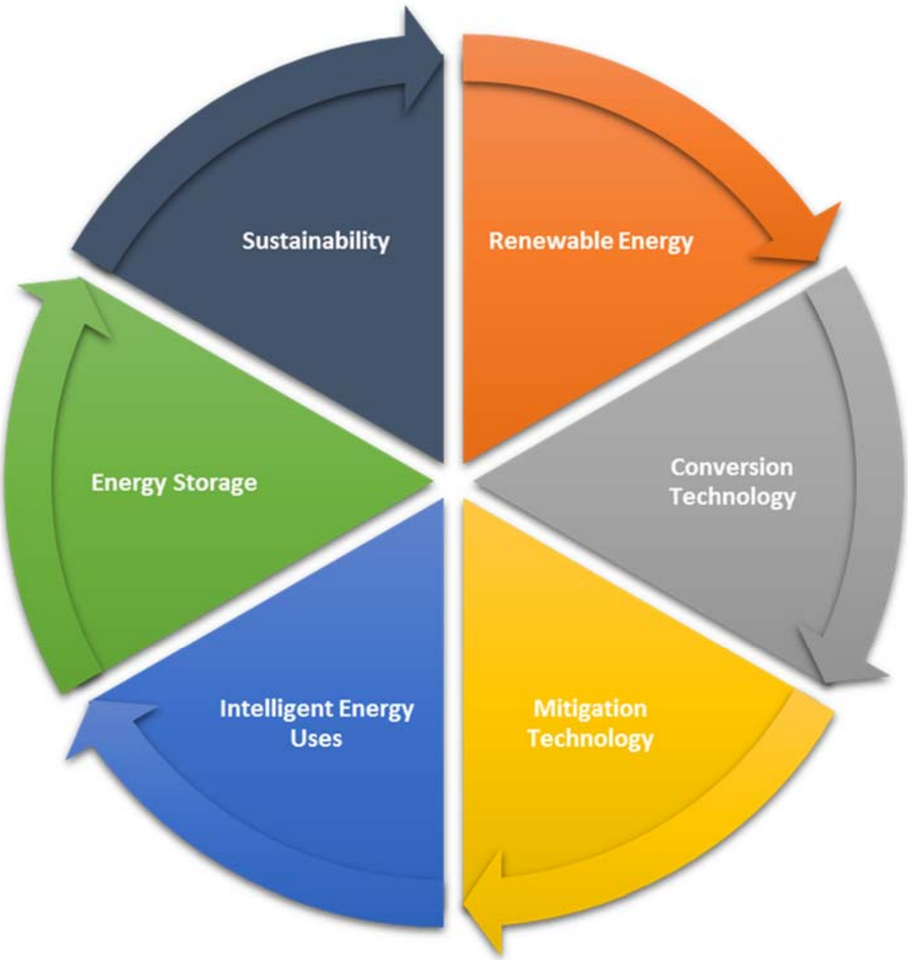

Figure1: Main areas covered by OptiCE.

Originally, the model included solar photovoltaic (PV), wind turbine, diesel generator, and battery bank for off-grid applications, in particular for PV water pumping irrigation [2]. The model has been continuously developed and new power sources, power-to-heat conversion technologies, and storage systems have been developed and integrated.

Opti-CE is an essential tool for researchers, consultants and decision makers working in the fields of renewable energies, hybrid power systems, distributed energy generation, and mini/microgrids.

2 Model description

OptiCE is composed by 10 files as shown in Figure 2. OptiCE can be used for both hybrid system simulations and optimizations. In the current version, OptiCE can simulate hybrid PV-wind-battery-diesel systems. The relationship between simulation and optimization mode and related files is summarized in Figure 3.

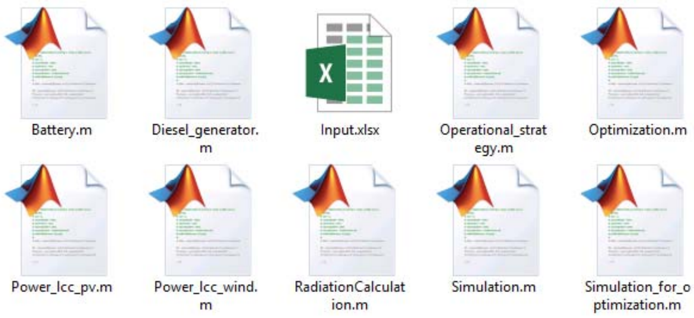

Figure 2: Files in OptiCE

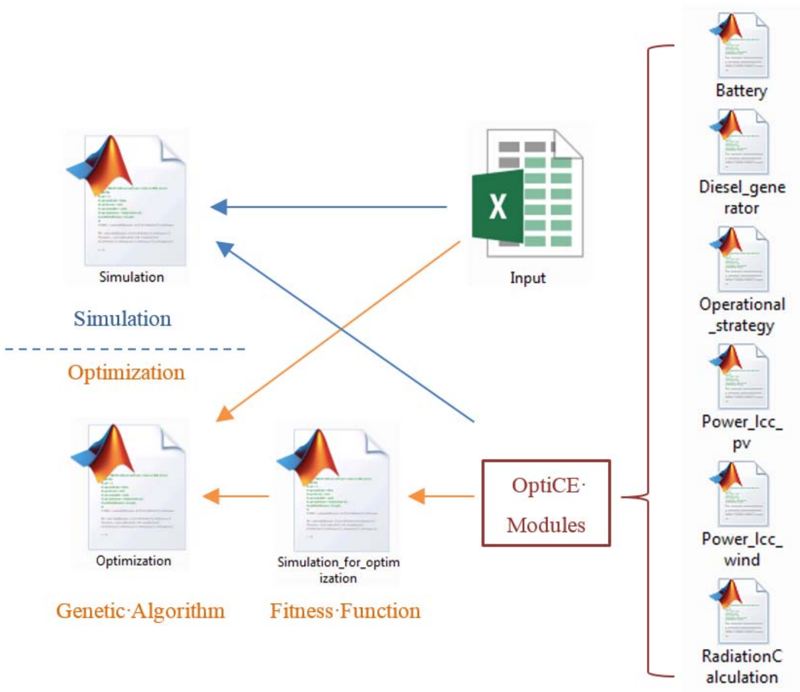

Figure 3: Simulation and optimization files in OptiCE.

2.1 Simulation

In the simulation mode, 'Simulation.m' will be used. The first section of the code is reading input data from the MS Excel file named 'Input'. In the following section, the variables (Tilt angle, Azimuth angle, etc.) in the system are declared and assigned with values. The last section starts the simulation, during which several functions need to be called: OptiCE Modules.

A brief description about the simulation process is as follows: Photovoltaic production profile is calculated with function ‘RadiationCalculation’ and ‘Power_lcc_pv’; wind power production profile is obtained from function ‘Power_lcc_wind’; the renewable power output profile, together with battery capacity, is fed into the function ‘Operation_strategy’, which carries out simulation of the annual 8760 hours and outputs the battery state of charge profile and grid power profile; the system reliability and life cycle cost are further calculated and the simulation is terminated.

2.2 Optimization

In the optimization mode, ‘Optimizaiton.m’ will be used. Same as ‘Simulation.m’, the first section of the code deals with data input from the MS Excel file. The second section carries out optimization. The employed optimization method is Genetic Algorithm (GA). During the optimization, the fitness function, which is ‘Simulation_for_optimization’, is called by GA. The fitness function defines the variables of interest and the objectives that need to be optimized. The input data from the reading section is also fed the fitness function. The fitness function is the same with the third section of ‘Simulation.m’ except that it is a function rather than a part of the script. The simulation process in the fitness function is the same with ‘Simulation.m’.

GA is a popular meta-heuristic optimization method, which can be used for both constrained and unconstrained problem. It is based on a natural selection process that mimics biological evolution [3]. The terminology related to GA, including individual, generation, population, Pareto front, etc. can be found with detailed explanation in [4]. The users are also recommended to know the basic of GA concepts and working principles. To customize the GA, the users are recommended to read the Matlab document [5] to familiarize with the syntax and options. Please notice that there is an update in Matlab 2016a, which makes the GA syntax different with previous Matlab versions. The GA configuration in OptiCE is shown in Figure 4.

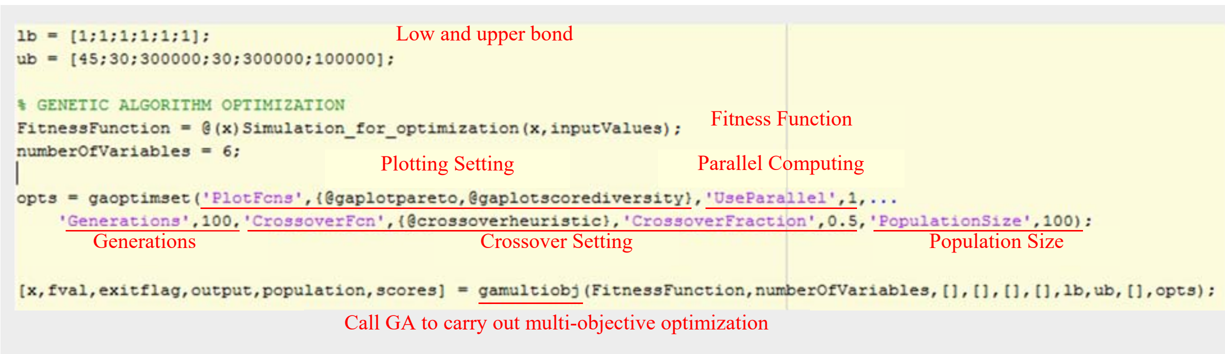

Figure 4: Genetic Algorithm configuration in OptiCE

3 OptiCE modules

3.1 Solar radiation calculation

The total solar radiation $G_{g,t}$ (W/m^2) depends on the horizontal radiation, surface orientation and it is given by three different contributions: beam radiation $G_{b,t}$ (W/m^2), diffuse radiation $G_{d,t}$ (W/m^2) and reflected radiation $G_{r,t}$ (W/m^2):

$$G_{g,t} = G_{b,t} + G_{d,t} + G_{r,t} \tag{1}$$

The beam component of the global tilted radiation can be calculated from the horizontal radiation through the following equation presented in Duffie et al. [6]:

$$G_{b,t} = \frac{G_{g,h} - G_{d,h}}{\cos(90 - \alpha)} \cos(\theta) \tag{2}$$

Where, $G_{g,h}$ is the global horizontal radiation (W/m^2), $G_{d,h}$ is the diffuse horizontal radiation (W/m^2), α is the solar altitude (˚) and θ is the angle of incidence (˚). The angle of incidence θ, function of the declination angle δ (˚), latitude φ (˚), tilt angle β (˚), azimuth angle γ (˚) and hour angle ω, has been computed according to the procedure described in Duffie and Beckman [6]. The diffuse component is given by:

$$G_{d,t} = G_{d,h} \frac{1 + \cos(\beta)}{2} \tag{3}$$

The ground reflected radiation is given by the following relation:

$$G_{r,t} = \rho_g G_{d,h} \frac{1 - \cos(\beta)}{2} \tag{4}$$

Where, ρ_g is the ground reflectance. The hourly values of the global horizontal radiation and of the diffuse horizontal radiation have been taken as input for the solar radiation model.

3.2 Photovoltaic system

The hourly simulation of the photovoltaic (PV) system is carried out through the following equation modified from Duffie and Beckman [6]:

$$P_{PV} = \eta_{PV,STC} \left[1 + \frac{\mu}{\eta_{PV,STC}}(T_a - T_{STC}) + \frac{\mu}{\eta_{PV,STC}} \frac{9.5}{5.7 + 3.8v} \frac{(NOCT - 20)}{800} (1 - \eta_{PV,STC}) G_{g,t}\right] A_{PV} G_{g,t} \tag{5}$$

where, P_{PV} is the hourly power output from the PV system (W), $\eta_{PV,STC}$ is the efficiency of the PV module at standard test conditions (STC) (%), μ is the temperature coefficient of the output power (%/°C), T_a is the ambient temperature (°C), T_{STC} is the standard test conditions temperature (25°C), v is the wind speed (m/s), *NOCT* is the nominal operating cell temperature (°C), A_{PV} is the PV array area (m^2) related to the array power peak, and $G_{g,t}$ is the global solar radiation on the tilted surface (W/m^2).

3.3 Wind system

The actual wind turbine power output P_{WT} (kW) can be expressed by the following as [7]:

$$P_{WT} = \begin{cases} 0 & (v < v_i \; and \; v > v_o) \\ \frac{1}{2}\eta_m \eta_e \rho A C_p v^3 & (v_i \leq v \leq v_r) \\ P_{WT,r} & (v_r \leq v \leq v_o) \\ 0 & (v < v_i \; and \; v > v_o) \end{cases} \tag{6}$$

Where, v_i, v_r and v_o are the cut-in, rated and cut-out characteristic speeds of the wind power curve (m/s), ρ is the air density (1.225 kg/m^3), A is the rotor area (m^2), C_p is the power coefficient, v is the actual wind speed (m/s), and $P_{WT,r}$ is the wind turbine rated power (kW).

3.4 Battery model

The battery model calculates the state of charge of the battery SOC_{bat} according to the following two equations for charging and discharging respectively [8]:

$$SOC_{bat}(t) = SOC_{bat}(t-1)(1-\sigma_{sd}(t)) + \left[P_{PV}(t) - \frac{P_{load}(t)}{\eta_{inv}}\right]\eta(charging) \tag{7}$$

$$SOC_{bat}(t) = SOC_{bat}(t-1)(1-\sigma_{sd}(t)) + \left[\frac{P_{load}(t)}{\eta_{inv}} - P_{PV}(t)\right]\eta(discharging) \tag{8}$$

where, t indicates the time step at which the parameter is calculated (hours), σ_{sd} is the hourly self-discharge rate, P_{load} is the power consumption (W), η_{inv} is the inverter efficiency (%), and η is the battery bank efficiency (%).

3.5 Operation Strategy

The operation strategy of OptiCE is shown in Figure 5. At time t, the renewable power production from PV panels and wind turbines is compared with the load. If there is excess of electricity production, the battery is charged. If there is excess of electricity and the battery is fully charged, the excess of electricity is dumped (in the off-grid systems) or exported to the external grid (in grid-connected systems). If the renewable electricity production is lower than the load, the battery is discharged. If the renewable electricity production is lower than the load and the battery is fully discharged, the load is met using either a back-up generator or the electric grid.

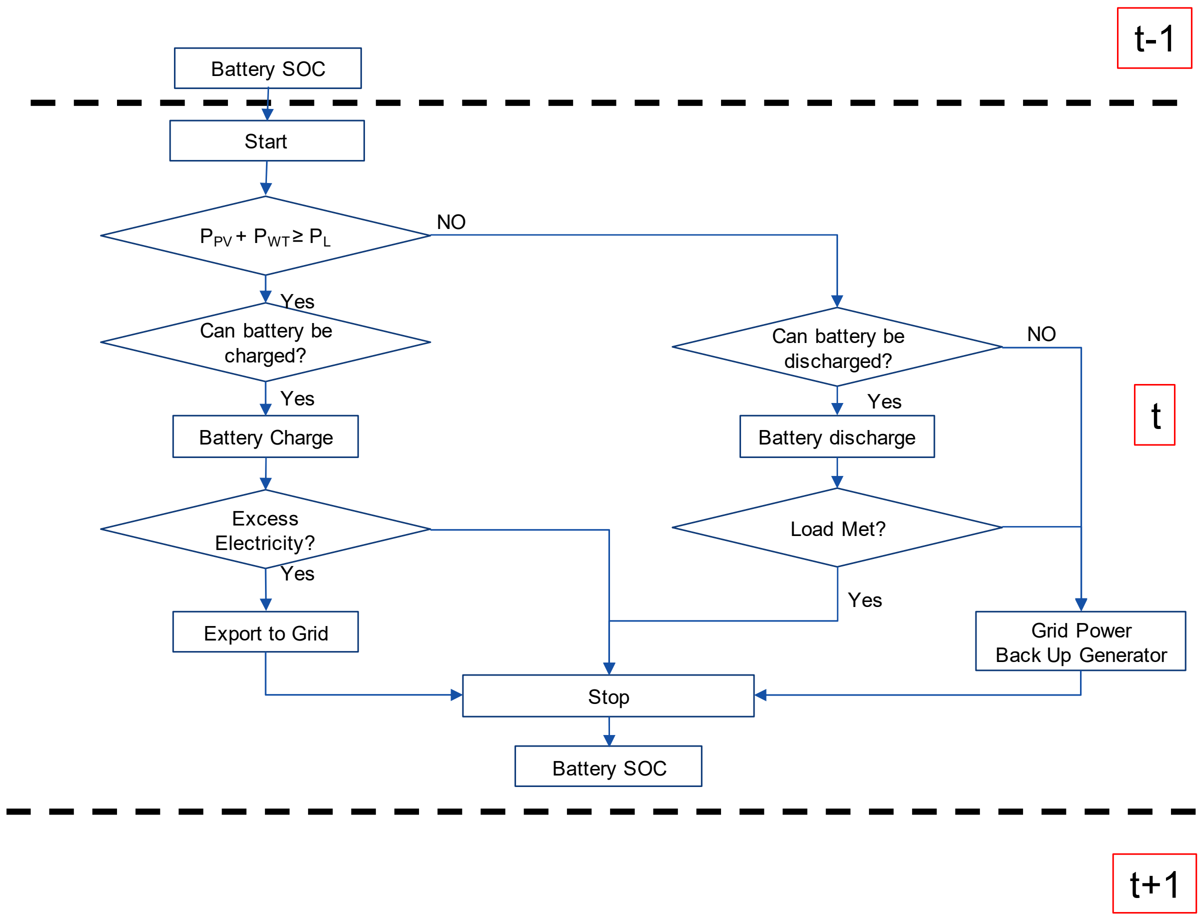

Figure 5. OptiCE operation strategy

3.6 Diesel generator model

The fuel consumption of the diesel generator FC_{DIESEL} (l) is calculated assuming the following linear relationship [9]:

$$FC_{DIESEL} = \alpha P_{DG+}\beta P_{DG,R} \tag{9}$$

Where, α and β are experimental coefficients of the fuel consumption curve (0.246 and 0.08145 l/kW h, respectively), P_{DG} is the power output of the diesel generator (kWh), and $P_{DG,R}$ is the rated power output of the diesel generator (kWh).

3.7 Optimization objectives

The optimization model maximizes the system reliability REL (%) and at the same time minimize the life cycle cost LCC (US$). REL and LCC are given by [10]:

$$REL = \frac{H_{SL}}{8760}100 \tag{10}$$

$$LCC = ICC - \sum_{n=1}^{N} \frac{d_n}{(1+i)^n} tr + \sum_{n=1}^{N} \frac{a_n}{(1+i)^n}(1-tr) + \sum_{r=1}^{R} \frac{ICC_c}{(1+i)^{rl_c}}(1-tr) - \frac{s}{(1+i)^N} \tag{11}$$

Where, H_{SL} is the number of hours the renewable power sources with the support of the battery can meet the load during the year (hours), *ICC* is the initial capital cost of the system (US $), *N* is the lifetime of the project (years), *n* refers to the n-th year of the project (year), d_n is the annual depreciation (US $), *i* is the interest rate (%), *tr* is the tax rate (%), a_t is the annual maintenance and operation costs (US $), *r* refers to the *r*-th replacement with *R* total number of replacements during the lifetime of the project, ICC_c is the investment cost of the component *c*-th to be replaced (US $), l_c is the lifetime of the *c*-th component to be replaced (years), and *s* is the salvage value (US $). ICC_c and l_c are vectors of c-th components. The total number of replacements *R* is a function of the lifetime of the number of components to be replaced and thus function of the lifetime of the components and is given by the following equation for the PV system:

$$R = floor\left(\frac{N}{l_c}\right) - 1 \tag{12}$$

Where, *floor* is the Matlab® function that rounds a number to the next smaller integer. Taking into account the salvage value, Equations 12 avoids to carry out the last replacement of the PV system in correspondence of the end life of the project, assumed equal to the PV system lifetime. The total number of replacements *R* for the other components to be replaced is conservatively given by the following equation:

$$R = floor\left(\frac{N}{l_c}\right) \tag{13}$$

The depreciation has been assumed straight-line and salvage value equal to 10% of the ICC [11].

4 License

Copyright (c) <2016> <Pietro Elia Campana, Yang Zhang, and Jinyue Yan>

Permission is hereby granted, free of charge, to any person obtaining a copy of this software and associated documentation files, to deal in OptiCE without restriction, including without limitation the rights to use, copy, modify, merge, publish, distribute, sublicense, and/or sell copies of the Software, and to permit persons to whom OptiCE is furnished to do so, subject to the following conditions: The above copyright notice and this permission notice shall be included in all copies or substantial portions of OptiCE.

OptiCE IS PROVIDED "AS IS", WITHOUT WARRANTY OF ANY KIND, EXPRESS OR IMPLIED, INCLUDING BUT NOT LIMITED TO THE WARRANTIES OF MERCHANTABILITY, FITNESS FOR A PARTICULAR PURPOSE AND NONINFRINGEMENT. IN NO EVENT SHALL THE AUTHORS OR COPYRIGHT HOLDERS BE LIABLE FOR ANY CLAIM, DAMAGES OR OTHER LIABILITY, WHETHER IN AN ACTION OF CONTRACT, TORT OR OTHERWISE, ARISING FROM, OUT OF OR IN CONNECTION WITH OptiCE OR THE USE OR OTHER DEALINGS IN OptiCE

5 Past performances

OptiCE model has been already implemented for research and consultant activities regarding:

- Optimization of PV and hybrid water pumping systems for irrigation in China [2, 12];
- Optimization of PV/wind hybrid power systems for shrimp farm in Thailand [13, 14];
- Wind driven heat pump for detached houses in Sweden;
- Optimization of residential district in Gothenburg [15];
- Optimization of PV and wind systems equipped with different storage technologies to increase photovoltaic self-sufficiency and self-consumption in residential building in Sweden [16-18];
- Optimization of hybrid PV/wind/battery system for a farm in Sweden [19];
- Optimization of solar home system in Colombia [20];
- Optimization of irrigation for combating drought in the United States [21].

6 References

[1] OptiCE, http://www.optice.net/; [accessed 16-08-2016]

[2] P.E. Campana, H. Li, J. Yan, J. Zhang, R. Zhang, J. Liu, “Economic optimization of photovoltaic water pumping systems for irrigation”, Energy Conversion and Management 95 (2015) 32–41

[3] Genetic Algorithm. http://se.mathworks.com/discovery/genetic-algorithm.html; [accessed 11.8.2016].

[4] A. Konak, D.W. Coit, A.E. Smith, "Multi-objective optimization using genetic algorithms: A tutorial", Reliab Eng Syst Saf 2006; 91: 992-1007.

[5] gamultiobj, http://se.mathworks.com/help/gads/gamultiobj.html; [accessed 11-8-2016].

[6] J.A. Duffie, W.A. Beckman, “Solar engineering of thermal processes”, 3rd ed. Wiley; 2006.

[7] M. Lydia, S. Suresh Kumar, A. Immanuel Selvakumar, G. Edwin Prem Kumar, “A comprehensive review on wind turbine power curve modeling techniques”, Renewable and Sustainable Energy Reviews 30 452–460 (2014)

[8] A.B. Kanase-Patil, R.P. Saini, M.P. Sharma, “Sizing of integrated renewable energy system based on load profiles and reliability index for the state of Uttarakhand in India”, Renewable Energy 36 (2011) 2809e2821

[9] M.S. Ismail, M. Moghavvemi, T.M.I. Mahlia, “Techno-economic analysis of an optimized photovoltaic and diesel generator hybrid power system for remote houses in a tropical climate”, Energy Conversion and Management 69 163–173 (2013)

[10] M. Campbell, "The Drivers of the Levelized Cost of Electricity for Utility-Scale Photovoltaics," SunPower Corporation, February 2008.

[11] S. Mathew, “Wind Energy-Fundamentals, resource analysis and economics”, Ed. Springer, 2006

[12] C. Zhang, P.E. Campana, J. Yang, J. Yan , "Economic performance of photovoltaic water pumping systems with business model innovation in China", DOI: http://dx.doi.org/10.1016/j.enconman.2016.10.069

[13] W. Nookuea, P.E. Campana, Y. Tan, J. Yan “Hybrid power system for sustainable shrimp farm”, Renewable Energy Integration with Mini/Microgrid REM2016, April 19-21, 2016, Maldives

[14] W. Nookuea, P.E. Campana, J. Yan, “Evaluation of solar PV and wind alternatives for self-renewable energy supply: case study of shrimp cultivation”, Energy Procedia 88 (2016) 462 – 469

[15] P.E. Campana, S.J. Quan, F.I. Robbio, A. Lundblad, Y. Zhang, T. Ma, J. Yan, “Spatial optimization of residential urban district - Energy and water perspectives”, Energy Procedia 88 (2016) 38 – 43

[16] Y. Zhang, A. Lundblad, P.E. Campana, J. Yan, “Study on employing battery storages to increase photovoltaic self-sufficiency in a residential building of Sweden”, Energy Procedia 88 (2016) 455 – 461

[17] Y. Zhang, A. Lundblad, P.E. Campana, J. Yan , “Comparative study of employing battery and hydrogen storages to increase photovoltaic self-sufficiency in a residential building of Sweden”, Renewable Energy Integration with Mini/Microgrid REM2016, April 19-21, 2016, Maldives

[18] Y. Zhang, P.E. Campana, A. Lundblad, L. Wang, J. Yan, “The Influence of Photovoltaic Models and Battery Models in System Simulation and Optimization”, 8th International Conference on Applied Energy ICAE2016, October 8-11 ,2016, Beijing

[19] P.E. Campana, Y. Zhang, A. Lundblad, H. Li, J. Yan, “An open-source platform for simulation and optimization of clean energy technologies”, 8th International Conference on Applied Energy ICAE2016, October 8-11, 2016, Beijing

[20] F. Benavente, G. Lindbergh, A. Lundblad, P.E. Campana, Y. Zhang, S. Cabrera, “State of charge profiles estimation for small off-grid PV-battery systems in Bolivia”, 9th International Conference on Applied Energy ICAE2017, August 21-24, Cardiff, United Kingdom

[21] J. Zhang, P.E. Campana, T. Yao, Y. Zhang, A. Lundblad. F. Melton, J. Yan, “The water-food-energy nexus optimization approach to combat agricultural drought: a case study in the United States”, (In press) https://doi.org/10.1016/j.apenergy.2017.07.036