Microgrid Optimisation with the Energy Storage Integration Tool

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***Abstract*—In this paper the Energy Storage Integration Tool (ES-IT) that has been developed by DNV GL is presented, which allows for modelling the behavior of micro-grids with Renewable Energy Sources (RES), Energy Storage Systems (ESS) and conventional power generators. ES-IT is a python-based optimization tool for designing both islanded and grid-connected micro-grids, and for households with ESS. The optimization for system dimensions can be selected for achieving different goals and it allows for more robust and efficient micro-grid architectures to be used. The ES-IT tool enables system developers to design a sustainable micro-grid to provide customers in remote areas and islands with cost-effective, sustainable and reliable electric power, focusing on RES and hence minimizing dependency on fossil fuels. In this paper, the tool and its capabilities together with the model inputs and outputs are described. Moreover, a comparative study that has been performed using the ES-IT tool for two case studies is presented. Finally, the two projects which are SOPRA (Sustainable Off-grid Powerstation for Rural Applications) and CSGRIP (Cellular Smart Grids Platform), within which the ES-IT tool has been developed, used and validated are discussed.**

Keywords- Micro-grid; Solar Photovoltaic; Energy Storage Systems; Diesel Generator; Optimization

I. INTRODUCTION

Increasing the share of Renewable Energy Sources (RES) while reducing the dependency on fossil fuels for power generation constitutes a challenging topic. The key reason for that lies on the introduced variability that characterizes RES (solar and wind), due to the dependency on weather conditions. It is essential to focus on robust and efficient micro-grid designs and architectures for hybrid power systems used to realize applications for remote villages, islands or isolated areas, where weak grid connection creates an additional barrier.

The rural electrification issue is not a rare one. Globally, approximately 1.6 billion people do not have electricity and clean water [1]. For many of these people, connection to public utilities is not economically feasible. However, RES provides a cost efficient and abundantly available source of energy that can potentially serve as a solution for the rural electrification problem, if used within appropriately designed micro-grid architectures. Moreover, ESSs enable the maximization of RES in such applications [2]. Important issues need to be addressed though, such as optimizing the lifetime of the hybrid system as well as optimal dimensioning of the ESS in combination with RES. Additionally, in order to enable the design of an efficient micro-grid that requires fewer or no conventional power generators such as Diesel Generators (DG), it is important to provide insight into the impact of ESS in combination with RES.

To tackle these challenges, the Energy Storage Integration Tool (ES-IT) has been developed by DNV GL as a solution to provide practical results for designing islanded or grid-connected micro-grids or households with ESS and conventional power generators. At first, this paper introduces the ES-IT model and its capabilities as well as the inputs and outputs of the model. In the following, a comparative case study for Burundi and the Netherlands is presented, where the ES-IT tool has been used for concluding the optimal micro-grid architecture according to various optimization goals. The simulation results are presented and discussed. Finally, the two projects within which the ES-IT tool has been developed, used and validated are presented and discussed in detail.

II. ENERGY STORAGE INTEGRATION TOOL (ES-IT)

A. *Model Description*

ES-IT is a python based optimization tool that provides practical results for the design of both islanded or grid-connected micro-grids and for households with ESS and DG. It constitutes a user-friendly and flexible tool that can aid solution providers by efficiently dimensioning the system components. ES-IT incorporates technical and economic models of ESS, Solar photovoltaic (PV) and wind systems as well as back-up DG. It can aid in designing robust micro-grid architectures by providing optimum configuration of the hybrid system through specifying the location and number of wind turbines, PV panels and ESS.

The optimization for system dimensions can be selected for achieving different goals, such as lowest costs, lowest emissions, maximum self-sufficiency or optimum battery life.

B. *Model Inputs*

The main inputs of ES-IT are the yearly profiles for the consumption of the connected users as well as yearly generation profiles for the connected RES (derived from weather profiles). The other vital input information constitutes the CAPEX cost figures of the ESS, PV, wind systems and the DG. Certain key characteristics of the ESS system, such as the C-rate (ratio between power and capacity), efficiency as well as cycle and calendar lifetime also need to be provided. The PV and wind system's lifetime and efficiency and DG's fuel costs, efficiency curve, start-up and stop time also constitute important model inputs. If certain information is not available, the model allows for default values to be extrapolated.

C. *Model Outputs*

After the execution of the simulation, the displayed results, that constitute the main output of the model are the system dimensions for the selected optimization goal. In addition, the yearly profiles of all system variables can be shown graphically, e.g. the battery power and energy content, or the diesel power. The optimization for system dimensions can be selected for achieving different goals, such as lowest costs, lowest emissions, maximum self-sufficiency or optimum battery life. The hybrid system dimensions can be provided for systems with or without backup DG (the latter meaning 100% RES integration). Furthermore, a sensitivity analysis is included, allowing for expert assessment of the model results. This means that the user can select a solution that is sub-optimal according to the model, but may be more suitable because of other conditions (e.g. geographical) that are not in the model. The calculation time is dependent on the settings and is in the range of a few seconds. An overview of the ES-IT model along with the inputs and possible system dimensioning optimization are shown in Figure 1.

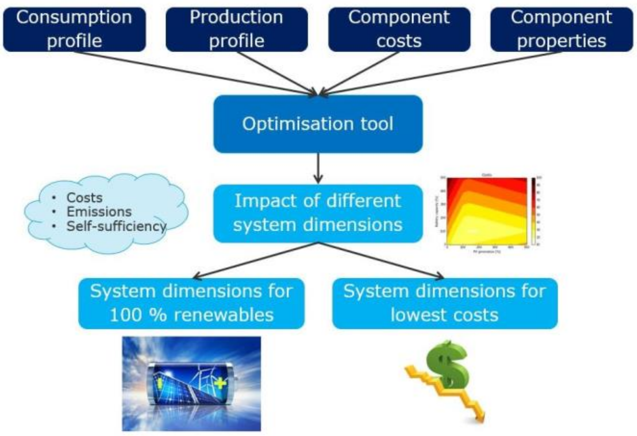

Figure 1. Energy Storage Integration Tool (ES-IT) block diagram

III. Case Study and Simulation Results

In this section, a comparative study that been performed for the geographical location of Burundi and the Netherlands (based on 2 study cases in the SOPRA project discussed in Chapter IV.A) through the use of the ES-IT tool is presented. The ES-IT tool was used to assess the optimal micro-grid architectures (with ESS, PV and DG only on islanded mode) according to different optimization goals. The inputs provided to the model in each case together with the corresponding simulation results for the optimization goals of interest are presented and discussed in the following sections.

A. *Input Profiles*

The input profiles that have been used for the comparative study between Burundi and the Netherlands are presented in this section. The total energy consumption of a village of 670 households (including hospitals, schools, military facilities, etc.) is scaled to one household for the household consumption profile of Burundi as shown in Figure 2. For the Netherlands household consumption, the total energy consumption of 60 households are scaled to one household. The corresponding daily household consumption profiles for the two locations are depicted in Figure 2.

It should be noted that the average daily household consumption for Burundi is 0.4 kWh while the average daily household consumption for the Netherlands is 9.6 kWh.

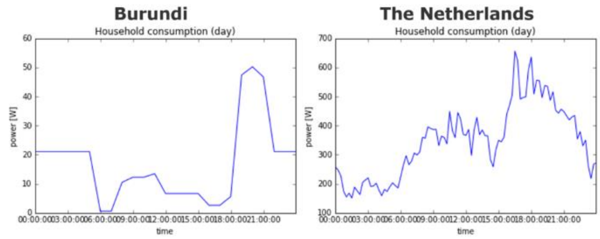

Figure 2. Daily household consumption for Burundi and the Netherlands

For this case study, only PV production profiles have been used. The annual PV production profiles for Burundi and the Netherlands are shown in Figure 3.

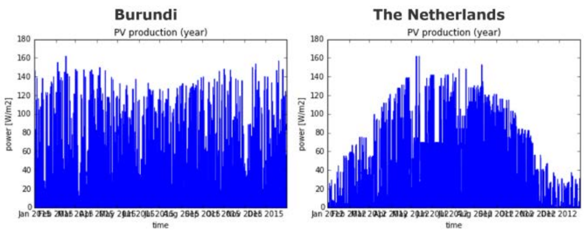

Figure 3. Annual PV production for Burundi and the Netherlands

If a 1 kWp PV installation size is considered, the yearly PV production for Burundi is 1538 kWh/year and for the Netherlands 950 kWh/year.

B. *Simulation Results*

Simulations have been performed using the ES-IT tool and the main results are presented in section III.B.1), III.B.2) and III.B.3). Focus was placed on maximizing self-sufficiency and minimizing costs, thus more analytical results are presented for these two optimization goals (yearly power profiles are not shown in this analysis).

For all output graphs, the PV generation percentage axis represents the percentage of annual generated electricity in comparison with the annual electricity consumption, while the battery capacity percentage axis represents the battery capacity scaled to the average daily electricity consumption. Moreover, PV generation at 100%

corresponds to zero-on-the meter, thus production and consumption are equal over a whole year, but not at any moment in time. Finally, battery capacity at 100% corresponds to battery capacity equal to the energy consumed on an average day.

1) Optimization Results for Minimized Costs

In Figure 4, the optimization results for minimizing the costs are presented for Burundi and the Netherlands.

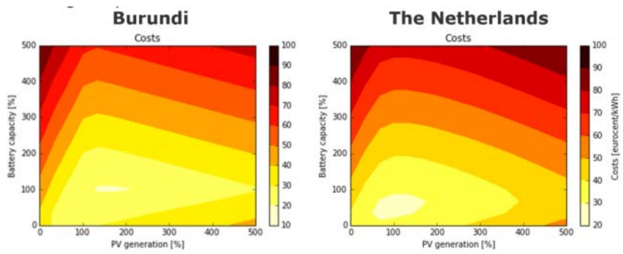

Figure 4. Optimization results for achieving minimum costs for Burundi and the Netherlands

As seen in Figure 4, in both locations (compared to diesel only mode) energy costs are reduced if a hybrid power system of storage and solar PV is used. A combination of at least 100% of PV power and up to 100% of battery capacity leads to the most cost-effective solution. It is noted that the optimum energy cost for The Netherlands will be below 30 eurocents and the optimum for Burundi will be below 20 eurocents. For comparison: the electricity costs with diesel generation only are equal to 0.35 €/kWh in this model.

More analytical information for this comparative study is provided in Table 1.

TABLE 1. KEY SIMULATION RESULTS FOR MINIMIZING THE COSTS

Parameter	Burundi	The Netherlands
Battery capacity	100 %	67 %
Battery capacity per household	0.4 kWh	6.4 kWh
PV generation	166 %	100 %
PV system rating per household	0.2 kWp	3.7 kWp
Electricity costs	0.19 €/kWh	0.28 €/kWh
Emissions reduced	88 %	60 %
Self-sufficiency	90 %	60 %
Annual battery cycles	325	200
Curtailment	35 %	35 %

2) Optimization Results for maximization of self-sufficiency

In Figure 5, the optimization results for maximizing the self-sufficiency are presented for Burundi and the Netherlands.

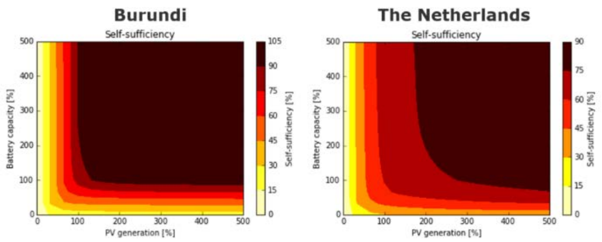

Figure 5. Optimization results for achieving maximum self-sufficiency for Burundi and the Netherlands

In general, 100% self-sufficiency needs a large PV system and a large battery, both need to be larger than 100%. For Burundi, this is technically feasible, with similar costs as with the diesel generator (that is twice the cost of the lowest cost option, see the previous case). However, for the Netherlands 100% self-sufficiency is not feasible and it results in very high costs.

TABLE 2 KEY SIMULATION RESULTS FOR MAXIMIZING SELF-SUFFICIENCY

Parameter	Burundi	The Netherlands
Battery capacity	255 %	1600 %
Battery capacity per household	0.9 kWh	153.3 kWh
PV generation	325 %	2000 %
PV system rating per household	0.3 kWp	73.6 kWp
Electricity costs	0.37 €/kWh	2.95 €/kWh
Annual battery cycles	158	18
Curtailment	70 %	95 %

3) Optimization Results for Minimizing CO_2 Emissions

In Figure 6, the optimization results for minimizing the CO_2 emissions are presented for Burundi and the Netherlands.

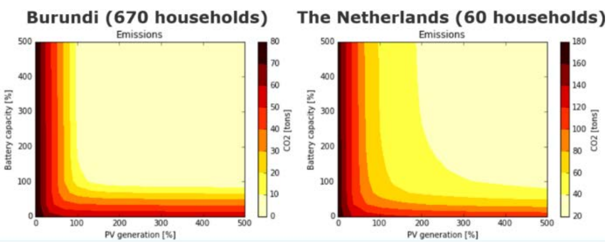

Figure 6. Optimization results for minimizing CO_2 emissions for Burundi and the Netherlands

It can be seen in Figure 6 that emissions are reduced by 80 tons by adopting optimum hybrid system configuration in Burundi and 180 tons in the Netherlands.

IV. RELEVANT PROJECTS AND ES-IT MODEL

Examples of projects in which the ES-IT model has been used constitute the Sustainable Off-grid Powerstation for Rural Applications (SOPRA) project and the Cellular Smart Grids Platform (CSGRIP) project.
The SOPRA project constitutes a development project that was started by a group of Dutch industries and knowledge institutes. It focuses on developing a modular platform for renewable power supply in rural areas.

The CSGRIP project, which succeeded the SOPRA project, constitutes a collaborative project supported by the Dutch government. This project develops a smart microgrid with power-frequency control and local demand-supply balancing by using ESS. The local power frequency is the control signal for coupling multiple microgrids, thereby reducing the need for a communication network.

A more analytical description of the SOPRA and CSGRIP projects is provided in the following sections, together with examples of how the ES-IT tool was used within these two projects

A. *SOPRA Project*

The Sustainable Off-grid Powerstation for Rural Applications (SOPRA) project is a development project that aims at developing a modular platform for rural power supply. This platform is based on the Multi-Source Hybrid Inverter (MHI) that has been developed in the Netherlands, combined with an electricity storage system. The MHI enables the design of a modular rural power supply system with any number of power sources of different kinds, e.g. solar PV, wind, DG, thus constituting the SOPRA system a more sustainable alternative for an existing DG power plant.

The first application is aimed at remote villages in developing countries, but the SOPRA system could also be applied on islands and in other isolated areas all over the world. The SOPRA system is a more sustainable alternative for an existing diesel generator plant. Apart from the innovative MHI, the system uses off-the-shelf components for generation and storage, delivered by the partners from the SOPRA consortium.

In the project three demonstration sites with different combinations of power sources are set-up to prove the feasibility of the SOPRA system. One of the demonstration sites is located at the HAN University in the Netherlands. The demo site is meant to demonstrate the use of energy storage to maintain distribution power quality in a grid with a large share of distributed renewable energy sources.

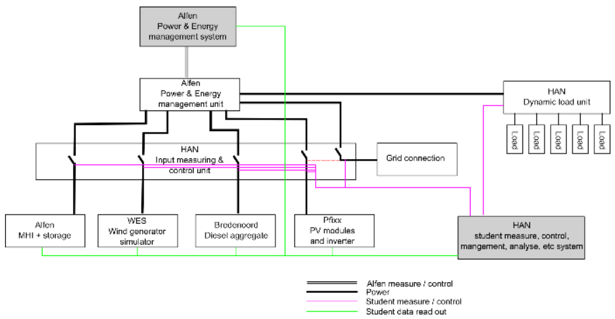

Figure 7. Layout of the demonstration site

In the off-grid system components of renewable energy such as a wind turbine and photovoltaics are integrated as well as other additional components like storage systems, a diesel generator and the MHI. Dynamic loads can be applied to the whole system, which is monitored by a Power & Energy management unit. The general system layout of the HAN demonstration site is depicted in Figure 7. The ES-IT model was used within the SOPRA project in order to conclude to the optimal configuration of the SOPRA system, that includes the location and number of wind turbines, PV panels and storage system. The SOPRA system was designed according the optimal system dimensions provided by the ES-IT tool, allowing for validation of the tool through a realistic application, thus adding significant value to it. The set-up of the SOPRA system is depicted in Figure 8.

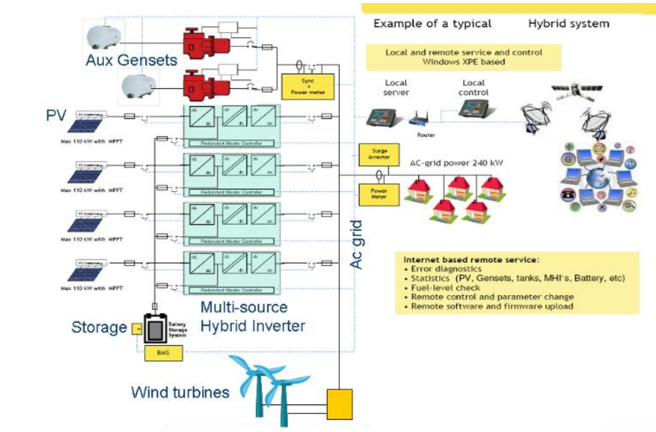

Figure 8. Set-up of the SOPRA system

B. *CSGRIP Project*

CSGRIP (Cellular Smart Grids Platform) is a collaborative project supported by the Dutch government. The CSGriP project aims at developing a smart grid concept to electrify remote areas with no or weak grid connection by maximally integrating Renewable Energy Sources (RES).

The concept of the CSGriP is based on its predecessor – the SOPRA project, whose primary objective was to develop a viable stand-alone system to supply power to remote areas in a secure and reliable manner. The goal of CSGriP is to take SOPRA a step further and build a stronger, robust and reliable grid by using power-frequency control of interconnected SOPRA cells as shown in Figure 9 [3].

Figure 9. SOPRA cell

In CSGriP, ways of interconnection of multiple SOPRA cells to form a stronger grid are explored, so that each cell can either work independently or in interconnected mode. Multiple cells can be interconnected through a backbone as shown in Figure 10. When multiple cells are connected with each other through a backbone network, it is termed as Interconnected mode. This kind of structure and philosophy for building a stronger microgrid is applicable in rural areas particularly in the case of developing countries.

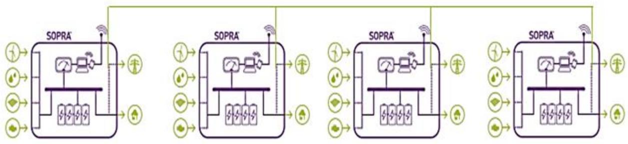

Figure 10 Multiple cells in interconnected mode [3]

The interconnected network of multiple cells can be further connected to the main external grid as depicted in Figure 11. Each individual cell can also be connected to the main external grid.

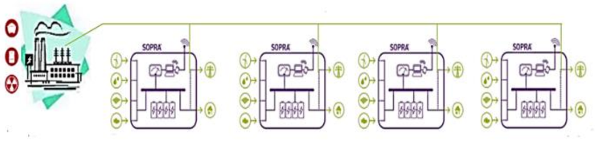

Figure 11 Multiple cells interconnected with main external grid [3]

The project hence develops a smart microgrid with power-frequency control and local demand-supply balancing by using ESS. The local power frequency is the control signal for coupling multiple microgrids (i.e. cells), thereby reducing the need for a communication network.

V. CONCLUSIONS

In this paper, the Energy Storage Integration Tool (ES-IT) and its capabilities have been analytically described, together with the inputs and output results. A comparative study between Burundi and the Netherlands is also presented together with the simulation results drawn from the ES-IT tool, that in essence provide the optimal system dimensions for the optimization goals of interest. Finally, the SOPRA and CSGRIP projects, within which the ES-IT model has been developed, used and validated, are described in detail. Through the abovementioned studies and realistic applications in which ES-IT tool has been used, it is proven that this tool enables system developers to design an optimized sustainable microgrid. In this way, they can provide customers in remote areas with cost-effective, sustainable and reliable electric power, focusing on RES and thus minimizing dependency on fossil fuels. More specifically, ES-IT aids solution providers by efficiently dimensioning the system components. Besides remote villages, military compounds, refugee camps and disaster response field hospitals could also benefit from having a rationally designed micro-grid.

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