Contrastive Techno-Economic Analysis Concept for Off-Grid Hybrid Renewable Electricity Systems

Based on comparative case studies within Canada and Uganda

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Abstract—**Both developed and developing countries share the same challenge of existing remote communities without electrical energy access, with respect to the tremendous difference in the percentage of such communities, and in the economic development status as well. Hybrid renewable energy systems (HRES) have the potential of playing a fundamental role in the global energy scenarios based on renewable resources, for grid-tied and especially for off-grid applications. This paper describes the research concept and shares project-related preliminary outcomes and experience for a contrastive techno-economic analysis and system design optimization of an Off-grid Hybrid Renewable Electricity System (OHRES). One of the main obstacles for accelerated expansion of off-grid energy systems is the lack of reliable data relating to system performance combined with economical system aspects due to the absence of standardization in technical and economic analyses. The objective is to understand how the technical, economic (taking into consideration the social implications on economic aspects) and environmental context in which an off-grid system is deployed affects its economic feasibility and sustainability. The methodology used in the research is comparing OHRES deployed in two case studies with contrastive economic and environmental conditions. The selected locations are in Canada and Sub-Sahara Africa in Uganda. An OHRES will be installed in each location combined with an off-grid remote system monitoring and weather station (SMWS). Both Case-studies were selected taking into account the technical common aspects as expected peak-loads range and off-grid system size have a reflection on having semi-identical system designs through using similar technologies with many common components for both case-studies, which serve the objective of carrying a contrastive system analysis. This study shall provide precise data on technically semi-identical systems in dissimilar scenarios, helping to achieve a more nuanced understanding of off-grid renewable energy systems in general.**

Index Terms—**Off-grid Hybrid renewable electricity systems (OHRES), stand-alone systems, hybrid battery storage, solar PV, small wind energy, techno-economic assessment, system design optimization, comparative assessment, off-grid remote system monitoring. Practical off-grid experience and lesson learned.**

I. Introduction

It has been a trending figure that 1.1 billion people worldwide are living without access to energy (or approximately one of each 5 persons). Traditional sources of fuel (e.g. coal, kerosene, etc.) are not only a hazard for environment compared to renewable resources, but also a serious hazard for humanity. 4.5 million premature deaths happens per year which can be ascribed to air pollution as a result from using such traditional sources of fuel [1] which are common sources of energy in so called developing countries. This is in addition to other serious effects which represents real hazards not only on the quality of life, but also on human life.

The need of energy is shared between both developed and developing countries. Still there are communities without access to especially reliable electrical energy taking place in both country types regardless of the countrys economic development indicators. Hybrid renewable energy systems (HRES) have the potential of playing a fundamental role in the global energy scenarios based on renewable resources, for grid-tied and especially for off-grid applications. On the other hand, the utilization of available renewable resource to achieve certain load demand is challenging, especially for fluctuating renewables like wind and solar PV from both technical and economic perspective.

The main vision for our study is to support the role of sustainable energy in providing energy access and help to end energy poverty worldwide. The research study is carried within the global initiative Affordable Energy for Humanity (AE4H) [2].The Affordable Energy for Humanity (AE4H) initiative is a global consortium of experts from academia and the private and public sectors that undertakes research, advocacy and knowledge transfer activities to advance Sustainable Development Goal 7 (as declared by the UN): ensuring access to affordable, reliable, sustainable and modern energy for all by 2030. Participating AE4H researchers advance knowledge across four domains: i) Generation, Devices, and Advanced Materials, ii) Micro-grids for Dispersed Power, iii) Information and Communication Technologies (ICT) for Energy System Convergence, and iv) Environmental and Human Dimensions of Energy Transitions. AE4H was established in 2015 as a partnership between the University of Waterloo and the Karlsruhe Institute of Technology(KIT). 140+ experts from 50+ organizations in 20+ countries participate in the initiative in various capacities. Such vision includes a wide range of technical, economical, environmental, social and political objectives which cant be covered all in one study. Our study is focusing on such off-grid hybrid systems from the techno-economic perspective, including various objectives.

The paper includes four main sections: First section covers the studies overall scope and main objectives from both the technical and economical perspectives. Section 2 gives information regarding the selected case-studies in Uganda and Canada, including the selection criteria of those case studies, general overview on both locations and a load demand and load profile sample. The third section covers different system related techno-economic aspects as system topology, decision making methodology example, overview of our techno-economic optimization model and details about the used remote system monitoring and weather station. In the last section we focus on the case-study in Uganda. The last section includes information regarding a recent site visit to the case-study location where the weather station was deployed in a testing location, and some shared practical lesson learned from the field work experience.

II. Study Scope and Objectives

The main vision for our study is to support the role of sustainable energy in providing energy access and ending energy poverty worldwide. The research study is carried within the global initiative Affordable Energy for Humanity (AE4H) [2]. This vision includes wide range of technical, economic, environmental, social and political objectives which can't be covered all in one study.

One of the main obstacles for accelerated expansion of off-grid energy systems is the lack of reliable data related to system performance combined with economical system aspects due to the absence of standardization in technical and economic analyses.

Our main focus in the study is on the techno-economic aspects of off-grid Hybrid Renewable Electrical Energy systems (OHRES). Our objective is to understand how the technical, economic (taking into consideration the social implications on economic aspects) and environmental context in which an off-grid system is deployed affects its economic feasibility and sustainability. A basic principle of designing a supply system, is the economical, ecological and societal optimization of generator size, storage size, backup system under consideration of unmet load, surplus generation (dump), and load management [3]. Based on that we are targeting the optimization and assessment of a reliable and economically efficient OHRES solution which can support the deployment of such systems globally.

A techno-economic assessment of the fundamental differences between the selected contrastive case studies in remote areas in Canada and Uganda with a focus on the techno-economical aspects is needed as a first step toward identifying the common problems and challenges and propose possible solutions which comply with both cases from technological, economical and (if applicable) social, political prospectives. Innovative technical state-of-the-art concepts will be investigated as Hybrid storage for off-grid applications. For now our technical and economical are presented as following:

A. Technical objectives

- Design and operation optimization for wind/PV system with storage integration matching certain load needs with low loss of power supply probability in off-grid applications, and a minimum contribution of the backup system (e.g. Genset).
- Installed capacity optimization and trade-off analysis between the hybrid system components.
- Design optimization recommendations for system components, e.g. small wind turbine, storage topology, coupling system without the need of using DC-DC conversion.

B. Economical objectives

- Achieve system economic efficiency through low-cost driven system components combined with system reliability and investment risk reduction.
- Sensitivity analysis of the factors affecting the economic feasibility of HRES under both cases
- Feasibility study of off-grid hybrid systems in both cases with and/or without the consideration of support schemes and incentives.
- Investment and business cases evaluation through dynamic economic indicators as Net Present Value (NPV), Internal Rate of Return (IRR), Debt Service Coverage Ratio (DSCR), and Levelized Cost Of Electricy (LCOE) [4] [5].

III. Case Studies Overview and Selection Criteria

Both Case-studies were selected taking into account the common technical aspects as expected peak-loads range and off-grid system size. These similarities will have a reflection on having semi-identical system designs through using similar technologies with many common components for both case-studies. This will serve the objective of carrying a contrastive system analysis.

A. Summary of case-studies selection criteria

The selection of the contrastive case-studies is done based on the detailed criteria described in table I. The distinction between developing and developed economies is based on the United Nations definition [7].

B. Case-studies overview

Table II summarizers some of the important details for the selected case-studies in Uganda shown in figure 1 and Canada shown in figure 2.

Fig. 1. Uganda Case-study location Sofraa Organization School in Wakisi, Jinja.

TABLE I
CASE-STUDIES SELECTION CRITERIA

Selection criteria / category for contrastive case-studies	Developed country	Developing country
Local partner or end customer related	Local partner has already a good understanding of renewable energy off-grid systems (Having already social acceptance and motivation for implementing an off-grid system)	Local partner has already a basic understanding of renewable energy off-grid systems (Social acceptance to be build up with the partner based on such basic understanding)
	Good (but not a must) to have a local partner with previously installed off-grid system (To represent how the system can perform based on previously experienced user)	Preferable to have a local partner with no previously installed off-grid system (To represent how the system can perform in an environment which lacks previous experience)
	Ownership and full control of the facility where the system will be installed should be represented in both case-studies (In order to limit external critical risks on the short and medium term of the project for the purpose of use changes for the location or need to de-commission the system due to uncertainties in ownership)	
	Availability of very good communication channel (Critical criteria which will minimize the risk of project sustainability and also increase the efficiency of system implementation, maintenance and operation of the project life-cycle)	
Location selection	Case-studies must be in a clearly defined developed vs developing economies (In order to analyze the effect of economic and basic political influences on off-grid sectors)	
Environment and renewable resources	Case-studies represent a clear contrast in terms of environmental, economic and social conditions, which off-grid systems can be deployed within (To represent the extreme cases of off-grid systems implementation in order to cover the within range of cases)	
Renewable energy policy and support mechanisms	Availability of a general orientation and awareness about using off-grid systems in addition to national policy	Availability of basic renewable energy supportive policy and mechanisms, preferably within the off-grid sector (micro-grids, Standalone systems)
	(Will have an influence on many project aspects rather than the techno-economic ones, like logistics handling, certifications needed for components, mini-level of standards availability)	
Techno-economic aspects	Remote locations with no access to the grid or very high electricity tariffs. Preferably to be a part of the remote community (Will support the economic feasibility of the off-grid system and project sustainability aspects)	
	Both case-studies will depend on Hybrid off-grid systems consisting of solar PV and mini-wind (if feasibility) and electrical energy storage (Hybrid Battery storage) as a main source for electrical energy (Having similarity in the renewable energy resources used and system layout, which is needed for the comparative analysis)	
	Case-studies should be within the same energy consumption [kWh] tier, based on [6] of the World Bank recommended framework (System design and sizing will not differ much between the case-studies, which support the objective of doing a comparative analysis)	

TABLE II
CONTRASTIVE CASE-STUDIES OVERVIEW IN CANADA AND UGANDA.

Category	Developing country	Developed country
Location	Sofraa Organization Wakisi School, Jinja, Uganda (figure 1).	Household in Nemaiah Valley, BC, Canada (figure 2).
Access to Electricity	Approximately 20.4 % of the Ugandan population has access to electricity [8]. Uganda has one of the lowest electrification rates in Africa and comparably high electrical energy tariff, despite being one of the poorest countries in Africa[9]. Rural Population 83.6 % from the total Population.	Nearly 100 % of the Canadian population has access to electricity [8]. However, Canada has 239 remote communities that are not connected to the main grid and depend on diesel generators to satisfy electricity demand and could benefit from off-grid renewable energy.
Solar irradiance	Most of the Ugandan territory receives a solar irradiance between 1,825 kWh / m2 and 2,500 kWh / m2 per year[10].	The Nemaiah Valley receives an approximated solar irradiance between 1,660 kWh / m2 and 1,960 kWh / m2 per year[11].
Supporting programs	The Ugandan government is supporting the implementation of solar applications in the country by creating national support plans including financing mechanisms for consumers and system operators, duty exemptions for certain off-grid components, and stating quality standards[12][9].	Public and private sectors are working together in British Columbia to provide free energy efficiency guidance, installation of energy saving products and tailored home energy assessment by professional contractors for low income households[13].
Case-study End-User	School building with no electricity and water access.	Private household owner.
Level of experiences regarding off-grid renewable electricity	No previous access to electricity, lack of previous experience.	Running on an off-grid system (need to be upgraded due to load demands), experienced user.

Fig. 2. Canada Case-study location- private household in Nemaiah Valley, British Columbia

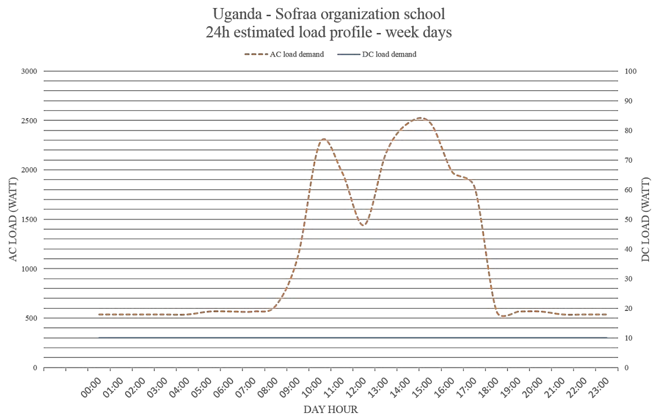

Fig. 3. Uganda case-study estimated load profile for 24h during week days

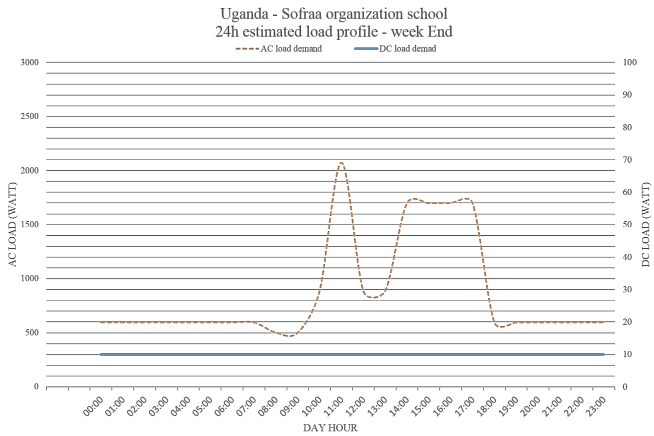

Fig. 4. Uganda case-study estimated load profile for 24h during week end

C. *Load profile and energy demand*

One of the most important factors which define the system technical design parameters is the load profile. In order to understand and estimate the load behavior in both case-studies, a load profile template was developed and used for collecting load information from both locations. The load estimation in the template is hourly based, and takes into consideration the possible total connected loads (TCL), and average connected loads (ACL) in each time step. Example of the load profile for the case-study in Uganda is illustrated Figure 3 and 4. The data was collected during a site visit survey to the school location in Uganda. The load behavior difference between the week-days (Monday to Friday) where the school is used in full capacity and the week-end where side activities only take place during the day. The type of loads connected are both AC and DC loads. The AC load categories are computers, projector, lights, fans and a pump. DC load is the self-consumption of the hybrid system. During week-days the total connected load peak is up to 2500 Watt, where during the weekend the peak demand reaches 2075 Watt. In the Canadian case-study the possible TCL peak demand is up to 2200 Watt. The type of loads used in the private household in the Canadian case-study are both AC and DC loads as well. The AC load are represented by washing machine, freezer, hair dryer, blender, computers, printer, TV, microwave oven, vacuum cleaner and radio. The DC loads are mainly lighting, with much lower share of the total load demand than the share of the AC loads. Both case-studies energy consumption (kWh/year) is within the tier-4 level of access in the multi-tier framework for household energy based on the World Bank recommendations (1319 - 2121 kWh/year) [6].

IV. SYSTEM TECHNO-ECONOMIC RELATED ASPECTS

A. *System design criteria and objectives*

A major challenge in the design of an off-grid system is the high level of variety such systems are exposed to due to the fact that each off-grid location can be unique and represents its own requirements which can vary from another off-grid location in the same country.In practice even this variation can be experienced on lower geographical levels within the same remote community. Such location based requirements are combined with the lack of standardization in such field, which result in the need of a custom made solution for each off-grid project.

Due to the above mentioned challenges, it is hard to select a major criteria for the system design which can fulfill the needs of all off-grid electrical energy supply problems. However, we have taken into consideration that the criteria of the system design have a major influence on related aspects of the final solution developed and provided to the consumer, especially the technical and economical related ones. As we are targeting a major objective of ending energy poverty through Off-grid solutions, our OHRES has to balance between five main major objectives as represented in figure 5:

- The system has to represent economic feasibility over its lifetime. This doesn't require by default having the lowest system initial cost, rather than ensuring the reliability and sustainability of the system performance and value stream income along the system lifetime.
- From the technical side, the system should be user friendly due to the targeted segment of developing economies end-users. This feature has to be validated with local case-study tests in target locations to ensure the common understating of the user needs and knowledge level.

- Simple system architecture is a key for system reliability and robustness as it will have a major reflection on the complexity level of the system operation and maintenance (O & M) activities. Especially in off-grid locations where a highly complicated O & M activity is economically totally not feasible due to many factors which vary from one off-grid location to another even within the same country. Most of these conditions vary even on lower geographical levels as mentioned before. System architecture level of complexity will also have a major influence on one of the challenging aspects of off-grid systems which is logistics and system handling for remote areas. System logistics could be an underestimated aspect in theoretical evaluations for off-grid electrical systems, this is due to the lack of practical experience in most of the research work done in this area so far. In practice logistics play a major role in the system deployment feasibility, and represents a main influencing factor on the off-grid systems economics.
- The other side of having a simple architecture system is taking into consideration the increase of system reliability and robustness. Such aspect is taken into account to ensure the sustainability of the system performance on long-term perspective, which will have a major influence on the system economics. In addition, building the trust between the end-consumers and the OHRES is elementary in developing country markets. Such trust is highly needed in order to boost the deployment of off-grid solutions in such markets where there is a high demand for these solutions.
- Safety is an nonnegotiable criteria for a system design, especially for electrical energy systems. Our system is taking such aspect into high consideration by paying good attention to the safety related aspects on both components and system level.

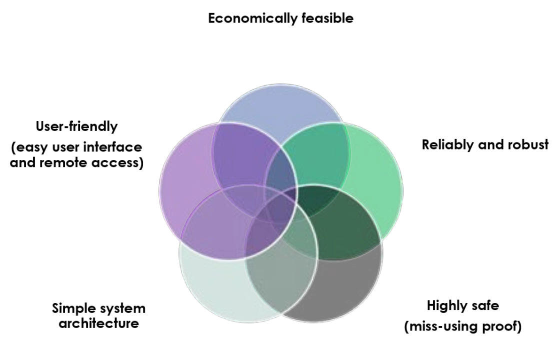

Fig. 5. OHRES technical design main objective

B. System topology and layout

Five major elements are the main building corners of most of the developed OHRES topologies.The first element is the renewable electrical energy sources. Followed by the non-renewable electrical energy sources. Third is the electrical energy storage element. Fourth is the supplied electrical load. Fifth is the system control and monitoring. These major elements represent together a complete OHRES which needs to be interconnected (coupled) to provide a physical platform for such elements to interact. The coupling method (for example AC coupling or DC coupling) of such systems depends on several system design aspects, which are highly related to which components are used in each of these five major system elements. In our system topology, we are using the state-of-the-art components for each of our system elements. In addition we are developing and testing together with industrial partners new technical concepts related to some of the components, especially in the energy storage and system remote monitoring and control parts. Our system topology is based on DC coupling, figure 6 illustrates the general layout of our system including all different components. A list of used components in each of the major system element is described in table III.

C. Decision making methodology for system technical aspects

Table IV summarizes an example for quantitative assessment of system DC voltage level using decision matrix analysis.

1) Decision matrix structure: The evaluation is done with a focus on the system size fitting with our case-studies energy demands as clarified before in the corresponding section. The methodology used is a decision matrix where each of the system voltage levels is quantitatively evaluated against all of the nine selected factors of the evaluation criteria. The decision matrix includes two main sections. First the evaluation criteria section, where different evaluation factors are listed and a weight is given to each of these factors based on its importance to our system design on a scale from 1 (least important) to 10 (highly important). The second section is the system DC voltage levels selected to be evaluated, in the shown case there are four voltage levels 12V, 24V, 48V and 110V DC. Each of the voltage levels is evaluated against all of the evaluation criteria factors, and evaluation points are used from a scale from 1 (lowest) to 5 (Highest) based on the fulfillment of the evaluated voltage level to the evaluation factor.

2) Evaluation criteria and evaluated voltage levels selection: The selection of the evaluation criteria factors and the voltage levels to be evaluated is done based on various off-grid field experts recommendations collected through direct interviews for project-based practical experiences. Beyond these recommendations, only the 110V DC voltage level was included in the evaluation. The reason is that this voltage level is for some of our tested Li-ion battery modules which can have good potential to be used as a battery storage solution within an OHRES, and need to be investigated. The evaluation points are quantified taking into consideration the current off-grid market actualities. A total quantitative score is collected for each of the evaluated voltage levels, and the system which gains the highest score represents the one matches most of the evaluation criteria. The details of the evaluation are included in table IV.

The evaluation outcome shows that the 48V DC system voltage level is the one matching best to the evaluation criteria compared to other voltage levels as shown in figure 7. It has been selected for the system technical design and products selection. The 24V DC which comes in the second

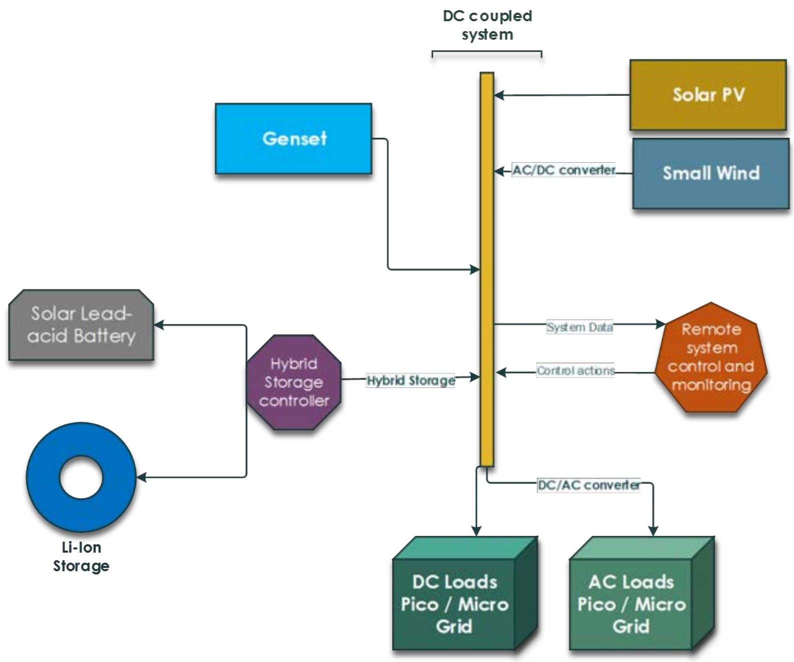

Fig. 6. Off-grid Hybrid Renewable Electricity System general topology

TABLE III
LIST OF USED COMPONENTS IN EACH OF THE MAJOR SYSTEM ELEMENT

System major element	Candidate technologies	Candidate components	Type of products
Renewable electrical energy sources	Solar PV, Small wind turbine	Mono or polycrystalline PV modules, Horizontal Access Wind Turbine (HAWT)	Standard state-of-the-art products (industrial partner Sunprism [14] for PV modules)
Non-renewable electrical energy sources	Genset	Diesel Genset or Gas (Propane) Genset	Standard state-of-the-art products
Electrical energy storage	Battery storage	Hybrid battery system lead acid combined with Lithium-ion (Li-ion) or Li-ion only battery	Developed in cooperation with our industrial partner BOS AG [15]
Remote system control and monitoring	Internet-connected controller and monitoring system	Data acquisition unit, Measurement sensors (V/ I sensors), Weather station, GSM modem	Developed in cooperation with our industrial partner Infinity Fingers [16]

place, followed by the 110V DC and the 12V DC system voltage has the least matching.

D. *Brief overview of the HMGS techno-economic model*

The internally developed Hybrid Micro Grid Systems (HMGS) techno-economic assessment model is based on the work of [17] developed originally for the assessment of standalone systems. In our study new boundaries, side conditions, a new optimization algorithm and techno-economic calculations are added to this model. The optimization aims to minimize the loss of power supply probability (LPSP), the levelized cost of electricity (LCOE) and to increase the share of renewables within grid-connected and stand-alone systems. This is achieved by finding the best composition of generation units and optimum energy storage operation mode under the given optimization goals. An alternative algorithm called Canonical particle swarm optimization Algorithm is used to solve this optimization problem. C-DEEPSO is a new population-based method built upon swarm intelligence and differential evolutionary technique. It is used as a solving algorithm instead of an original particle swarm optimization due to a higher robustness of results [2]. More details about the C-DEEPSO algorithm and its properties as wells as the HMGS model can be found in [18], [19], [20] and [21]. An overview of the optimization model is given in Figure 8.

Beside the HMGS model we are using Homer energy [22] for the hybrid electrical systems feasibility analysis and system sizing optimization.

E. *Remote system monitoring and weather station (SMWS)*

One of the most neglected aspects in most of the installed off-grid renewable electrical energy system is the ability to fully monitor, take control actions remotely and evaluate the system operational performance against the available renewable resources in the system installation area. In our technical system design we have taken into high consideration how to cover this gap, using a remote system monitoring

TABLE IV
DECISION MAKING MATRIX FOR OHRES DC VOLTAGE LEVEL SELECTION

Evaluated system level DC voltages		12V DC		24V DC		48V DC		110V DC	
	Evaluation factor Weight 1-10 (a)	Evaluation points 1-5 (b)	Quantitative score (a*b)	Evaluation points 1-5	Quantitative score	Evaluation points 1-5	Quantitative score	Evaluation points 1-5	Quantitative score
Evaluation factor weighting criteria scale	1 = Least important 10 = Highly important								
Evaluation points criteria scale	1 = Lowest value 5 = Highest value								
Evaluation Criteria									
Reduction of system losses	10	*1.5*	15	*3*	30	*4*	40	*5*	50
Using of cheaper cables with small cross section	5	*1*	5	*3*	15	*4*	20	*5*	25
Validity of price competitive system components specially MPPT and inverters	8	*2.5*	20	*5*	40	*5*	40	*0*	0
Off-grid components can handle more power in the same product category	10	*1.5*	15	*3*	30	*5*	50	*5*	50
Availability of a range of commercial off-grid component in the voltage range	10	*5*	50	*5*	50	*4*	40	*0*	0
DC loads (speciality lighting) availability in the market	4	*5*	20	*5*	20	*2.5*	10	*0*	0
Compatibility with the currently used DC loads (specially lighting) in the off-grid applications	4	*5*	20	*5*	20	*2.5*	10		0
Compatibility with commonly used commercial available li-ion storage systems	9	*2*	18	*2*	18	*5*	45	*5*	45
Can take advantage of future trend of development for the storage market	6	*2.5*	15	*2.5*	15	*4*	24	*5*	30
Evaluation score			178		238		**279**		200

and weather station (SMWS). The main components of the SMWS are as shown in figure 9:

- Self-powered commercial weather station
- Hall effect sensors (voltage / current measurement)
- Controller and data acquisition unit
- GSM Modem

Figure 9 shows the pre-commissioning lab testing setup of the SMWS. Each of these components provide a unique functionality and the different components are integrated together within the OHRES to provide a full remote monitoring and performance assessment functionality. The weather station provide the needed weather and available renewable resources measurements as: solar irradiation, wind speed, wind direction, ambient temperature, humidity, atmospheric pressure and PV module temperature. The station is self-powered using a small PV panel and integrated battery. Measured data is transmitted wireless to a wireless interface, which is connected to the controller and data acquisition unit. For the monitoring of the system functionality and flow of energy, Hall effect current and voltage sensors are

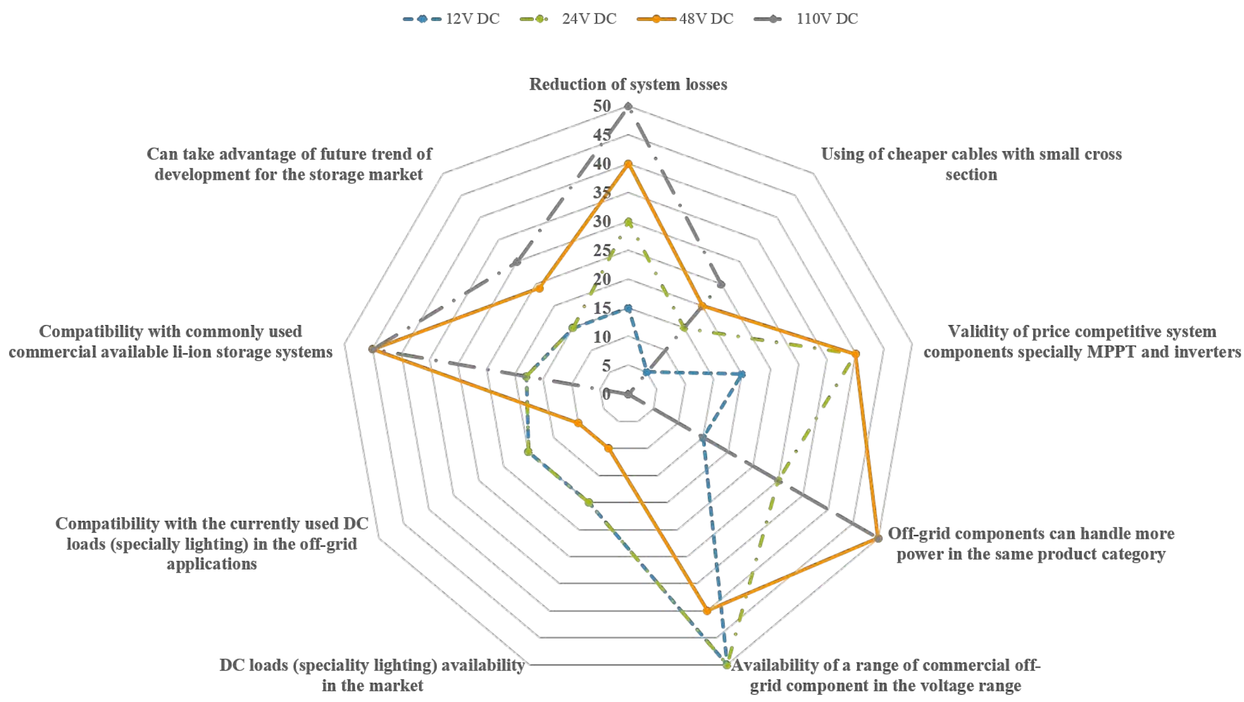

Fig. 7. OHRES DC voltage level - Quantitative assessment results

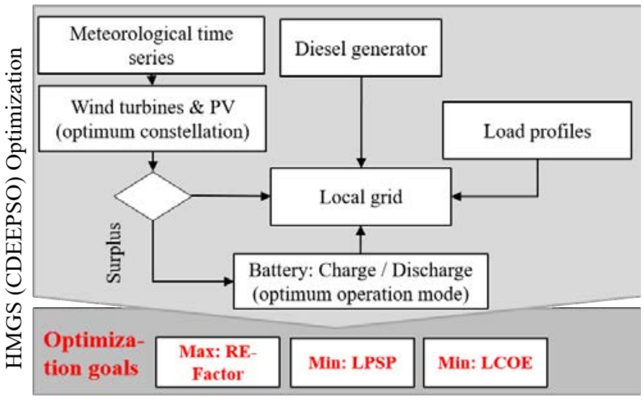

Fig. 8. Simplified model structure of the optimized Hybrid Micro Grid Systems (HMGS) model

used in selected system positions. The data from the weather station and the monitoring sensors are transmitted to the controller and data acquisition unit using Modbus RS485 as communication protocol. The controller and data acquisition unit was developed in cooperation with an industrial partner, and is capable of handling multiple functions within the system. In our system setup its main functionality is the data collection, cleansing, pre-processing and communication using Internet connection. The Internet connection can be provided using common LAN connection, GSM modem or satellite connection. One of the important functionalities of this unit is optimizing the size of data files sent remotely, in order to minimize the communication capacity needed which is a typical condition in most of the off-grid locations. The data transmitted is represented on a web based user interface which allows data monitoring and download, an example of the user interface is shown in figure 11.

V. UGANDA CASE-STUDY SYSTEM PHASE (1) DEPLOYMENT AND PRACTICAL LESSONS LEARNED

One of the most critical pre-requisites for a successful off-grid systems design is a very early site survey, due to the fact that each off-grid location is unique (as described before). This aspect is taken into high consideration in our study, especially for the developing country case-study in Uganda where is not enough information and data available which reflects the practical facts and challenges on the ground. In beginning 2018 a site visit was done to the case-study location in Uganda. The visit included several activities and objectives, each of these objectives has a list of needed actions in order to achieve the needed objective result (the detailed action plan is not shared here). The main objectives of the site visit can be summarized into four main categories as follows:

- Technical visit related objectives
  - i School location detailed site assessment and survey.
  - ii Installation and commissioning of the system first phase, the weather station in a selected testing location.
  - iii Having a preliminary assessment of the available renewable and non-renewable energy resources in the case-study area.
  - iv Selection of the OHRES different components (PV panels, battery storage system, small wind turbine, Control unit cabinet, SMWS) installation spots in the school location.
  - v Collecting a realistic impression and having a close practical view for the case-study technical needs (e.g. load distribution).
  - vi Commissioning of the remote data acquisition unit including the GSM modem and having a hot-running test of the data streams from Uganda to our database in Germany.
- Economical visit related objectives
  - i Survey the locally available renewable electrical energy financing mechanisms, with focus on small-scale systems for private owners.
  - ii Collecting preliminary general overview about the level of maturity for using off-grid systems especially within rural remote areas.
  - iii Having a realistic understanding for the financial capabilities of the targeted private owners for off-grid electrical systems in rural areas.
  - iv Getting in contact with governmental entities and representatives (if possible) to measure the real level of utilization for the off-grid applied support mechanisms, and its implication on the system economic feasibility.
  - v Check the level of market maturity and understanding for the economic aspects and investment nature of renewable energy projects in general, and in particular off-grid electrical energy systems.
- Social visit related objectives
  - i Measure the awareness regarding renewable energy.
  - ii Getting a close understanding of the social interaction in the case study location.
  - iii Experience the life-style of end-consumers through living in the same life conditions if possible.
- Project management related objectives
  - i Getting introduced and establish communication channels with the members of the local project partner Sofraa Worldwide Organization [23].
  - ii Building local support capacity (especially for technical troubleshooting) from selected local project partner members, who have basic technical capabilities and potential to receive a technical training.
  - iii Identification of reliable local partner companies in the field of renewable energy off-grid systems, and create mutual-interest for partnership within the case-study project scope.
  - iv Revise the project stakeholder analysis, especially the importance and influence of each of the stakeholder on real-life practical basis.
  - v Identify real risk potentials and possible practical mitigation methodologies for them.
  - vi Have an early estimation of the bottle-necks in the project life-cycle which can have major influ-

ence on the estimated project work break-down-structure and time-line.

A. Deployment of system phase (1) in Uganda

Figure 10 shows the deployment of the weather station and the remote data acquisition system, including a GSM modem for providing internet connection in Uganda. The weather station is installed for the hot-running test in a near secured testing location to its planned final installed location in the Sofraa organization school. It is planned that the weather station will be transfered to the final installation location once the school starts its full operation, which is planned for this year (2018). The weather station is self-powered using a PV panel and integrated battery for powering the sensors and externally installed components. The measured data from the sensors in the weather station is transfered using wireless communication to the weather station wireless receiving unit installed indoor. The data is transfered to the data acquisition and control unit using Modbus RS485 protocol. A GSM modem using the local GSM network provide Internet communication for the data transfer from the data acquisition and control unit to the data-bank. The data can be accessed and downloaded using an online web portal. Figure 11 shows a real example of how the data is illustrated on the web portal based on the data transfered from the weather station in Uganda. The SMWS and the data portal is developed in cooperation with our industrial partner Infinite Fingers [16].

B. Major lessons learned for phase (1) system deployment in Uganda

In this section we focus on only few selected practical learned lessons in Uganda. We delegate a full list of lessons learned with more detailed discussion to future work.

i **Test as much as possible prior to shipment**
It is an important pre-requisite to make (when possible) pre-commissioning and cold-run tests for different OHRES parts in a controlled environment (lab test, factory test or local prototypes) before sending it to the final off-grid location. This minimizes both the time and possibility of system failure to operate in the final remote location where there is almost no technical support or room for complicated troubleshooting.

ii **Some components would still represent a technical challenge**
For some of the OHRES parts, it is not possible to perform pre-commissioning and testing before sending them off-grid. Even some of the pre-tested components can represent a challenge for commissioning them in site location. For example, in our case such components included the GSM modem which is providing the Internet connection for the remote data stream flow from our remote location in Uganda to the database in Germany. Such components represent very high-risk sources on the success of achieving the objective of having an off-grid running system with remote monitoring. Unfortunately, there are no clear risk mitigation methodologies available for such risk sources due to the general lack of standardization in the off-grid sector, in addition to the lack of enough publicly shared practical field experience.

iii **Handling logistics in an effective way**
System logistics could be an under-estimated aspect in theoretical evaluations for off-grid electrical systems; this is due to the lack of practical experience in most of the research work done in this area so far. In practice, logistics play a major rule in the system

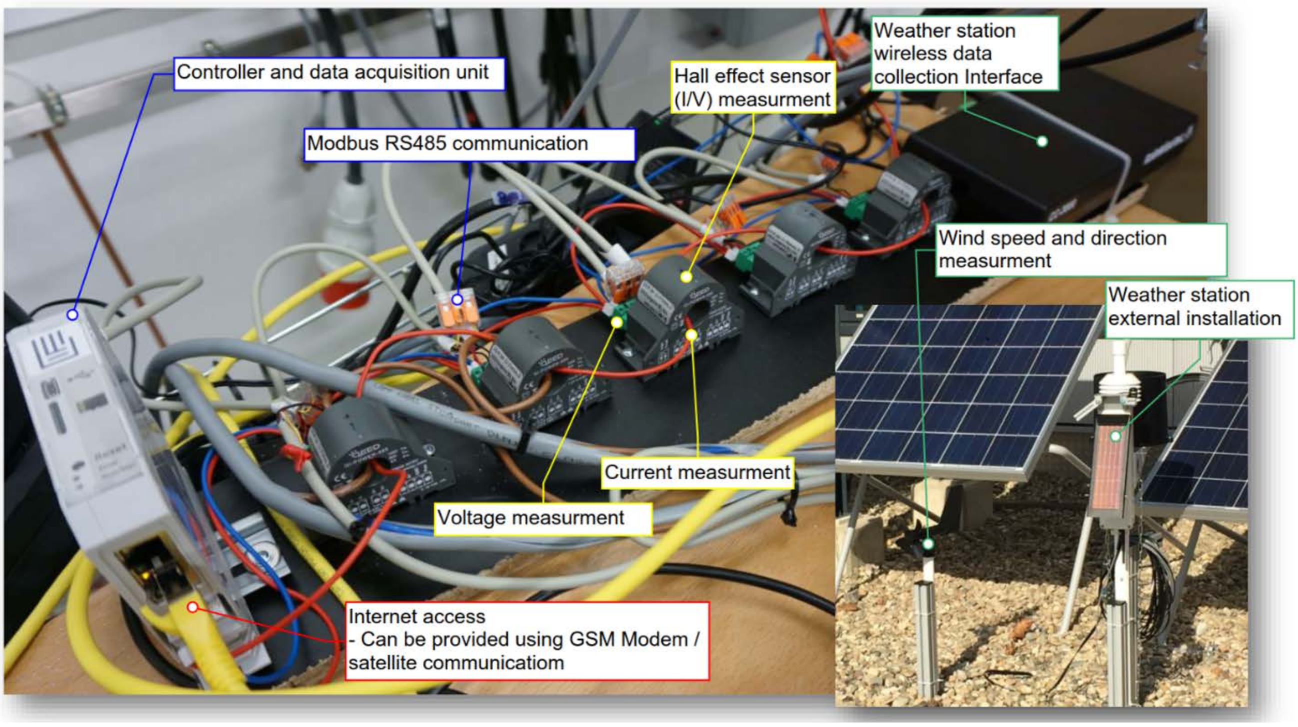

Fig. 9. Remote System Monitoring and Weather Station (SMWS) lab cold-running test

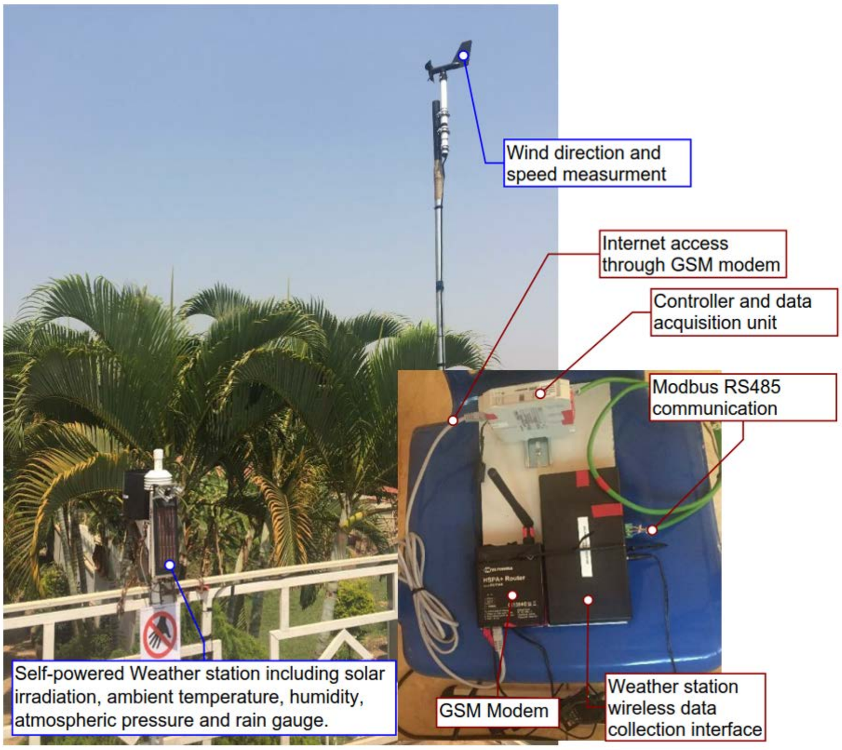

Fig. 10. Weather station and remote data acquisition commissioning and hot-running test in Uganda, Jinja

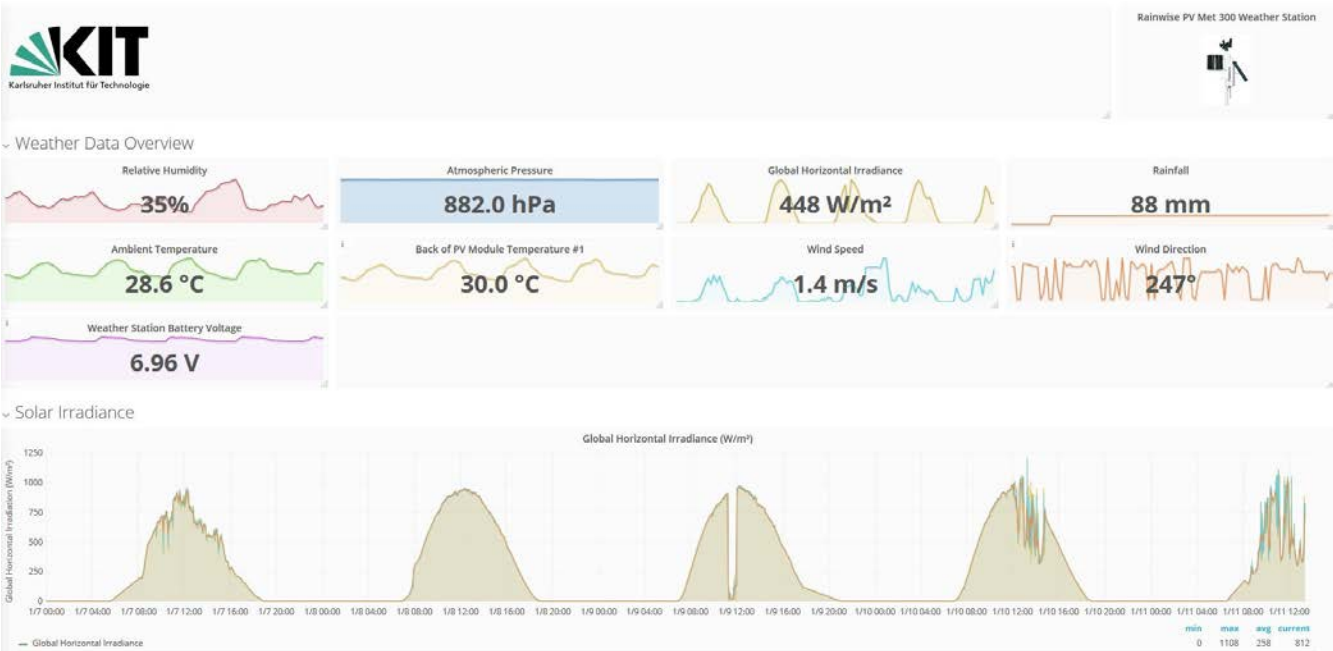

Fig. 11. Data monitoring and analysis portal for remote SMWS, developed in cooperation with our industrial partner Infinite Fingers [16]

deployment feasibility and represent a major influence on the economics of the off-grid system.

VI. Conclusion

The global energy access is a common challenge for both developed and developing countries, where there are still remote communities without reliable energy supply. OHRES provide a solution for a decentralized electrical energy supply in such remote communities. Using the comparative approach for contrastive case-studies supports overcoming one of the main obstacles in accelerated expansion of off-grid energy systems, namely, the lack of reliable data related to system performance combined with economical system aspects. Such reliable data will help fill the problem of standardization absence in the off-grid electrical energy field. Although the challenge faced for off-grid electrical systems includes a wide variety of technical, economical, environmental, social and political related factors, the main focus of our study was the techno-economic aspects in particular. We have presented our case-studies in Canada and Uganda, in addition to some of the techno-economics highlights for our OHRES and SMWS. Some of the lessons learned from the recent system deployment experience in Uganda show the importance of carrying early organized site visits with clear objectives as the one shared in this work. Our future work will include several practical and research activities: i) A site assessment for the Canada case-study is planned, ii) the pre-commissioning and lab testing of the system first complete prototype including the hybrid storage system and the SMWS, iii) Developing a data analysis platform, iv) Optimization of the HMGS techno-economic used calculation models, and v) The deployment of the two OHRES in case-study locations, which is a top priority for our study at the moment, in order to generate and collect the primary data needed for the study scope.

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