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A Systemic and Multi-disciplinary Diagnosis Model for Microgrids Sustainability Studies

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Abstract

There is a growing research interest in studying microgrids in rural areas as a means to promote energy access. These microgrids could be the key to energy access on a global scale because of their many advantages compared to classic grid expansion. Despite all these qualities, feedback from microgrids in rural areas shows that most fail to reach sustainability, but the reasons for their long-term failure are still not a consensus in the literature. This work intends to contribute to understanding microgrids' sustainability and their expansion by modelling them using a systemic vision approach. For this purpose, we propose a diagnosis tool that includes energy, financial, information and social aspects. A series of study cases are analyzed through this approach, showing it as a possible diagnostic tool for microgrids in the short and long term.

Keywords: Energy Modeling & Design, Grid System, Diagnosis, Rural Electrification, Sustainable Development, Systemic Approach

I. INTRODUCTION

According to the United Nations, 789 million people live with no access to electricity [1]. Without a more engaged action, 650 million people will remain without energy access by 2030 [2]. The investment required for universal energy access through grid expansion by 2030 will cost more than \$48 billion each year. In contrast, the technologies providing safe and clean electricity are now cheaper and more accessible than ever to the population [3], but rural electrification programs remain challenging endeavours. Because of the limited resources of its target users, rural electrification is well suited for a bottom-up approach where the grid starts small and expands over time together with its community resources and energy needs [4].

Microgrid expansion can take many forms, such as an increase in the number of users, increased energy production capacity, and increased subsidies from local authorities, among many possibilities.

This work uses a systemic approach to study these expansions and their impact on the microgrid.

Systemic approaches, such as the one proposed in the Macroscopic [5], allow a complex system to be represented by simple interactions among base fields. It calls for the study of the system and its thorough description through a multi-disciplinary canvas that yields its base fields.

This work proposes a novel microgrid modelling method based on a systemic approach, identifies its main fields and studies their interactions. This new microgrid representation adds value to how it links together different fields. These cross-field links are expected to bring a more general understanding of the microgrid, its operation, and its failures and be a more versatile tool for its study.

Many other models have been presented in the literature to consider a maximum of parameters for an interdisciplinary study of microgrids with different goals in mind. Carpintero-Renteria [6] makes a clear and complete state of the art of the operation of the microgrid with its model. Sachs [7] brings a sustainable business model solution for developing a microgrid. Akinyele [8] shows all the difficulties which can appear in various fields of microgrid development and sustainable solutions to counter them. Hicks [9] ultimately criticises the limits of microgrids. All these models have in common the systemic approach but failed to consider the possible exchanges between the fields in their analysis.

Section II provides an overview of the proposed meta-model. Section III introduces the fields represented in the meta-model. Section IV presents the diagnosis tool using the meta-model. Section V exposes an example of a real microgrid use case. Section VI finally, explore possible future works. ds its base fields.

II. Meta-model Overview

In rural electrification microgrid literature, the two most important definitions of microgrids are the "energy microgrid" and the "community microgrid".

The European Microgrids project [10] defines *microgrids* as "Low Voltage distribution networks comprising various distributed generators, storage devices and controllable loads that can operate either interconnected or isolated from the main distribution grid as a controlled entity". Three base fields can be derived from this definition, namely electrical, control, and communication.

A definition of community microgrids is given by Gui [11] as the following: "A community microgrid is connected with its community through physical placement and can be partially or fully owned by said community. [...] Considering the social dimension, a 'community microgrid' can be viewed as a microgrid with the key



objectives of achieving economic, social and environmental benefits in community electricity supply and distribution". Two extra base fields can be identified from this definition, namely social and financial.

In this work, four base fields will be used to represent the microgrid system: energy, information, financial and social aspects. Control and communication are merged into a single field as they handle the same type of object, information.

These four base fields define the challenges surrounding microgrid implementation. Such as the overall quality of the power grid equipment and operation, the value extraction of the data processed, the sustainable operation of the business model as well as the acceptance of the community during microgrid implantation.

Table 1. Description of the exchange between fields

To \ From	Energy	Information	Financial	Social
Energy	Energy flows	The data sent to the power grid for its control	All the investment that is brought for the good functioning of the power grid	The involvement of the users for the good usage of the microgrid
Information	All the data retrieved from the electrical grid in order to be processed by the different algorithms for the control or monitoring of the grid	Information flows	Investment for the improvement or maintenance for the good operation of the data and command processing equipment	Community's establishment and compliance with rules relating to the use of data generated within the microgrid
Financial	The economic productions linked to the operation of the microgrid and the energy consumption itself	All the data processed to provide a clear view of the health and operation of the microgrid for its management	Financial flows	Community's establishment and compliance with rules relating to the use of power grid and its pricing system
Social	Represents the impact of the electricity grid on the community through the consumption of energy	All the data processed in order to be able to provide a diagnosis of microgrid usage to the grid users	Follow-up and training of the community by the microgrid manager to ensure compliance with the established rules	Social interactions

The proposed meta-model links together the four base fields and is based on a series of definitions described as follows:

- **Field:** a fundamental block which composes the microgrid. They are bounded by four fundamental fields of expertise, namely energy, information, financial and social.
- **Flow:** A flow is an interaction between one or several elements of the same field.
- **Exchange:** An exchange is an interaction between one or more elements of two different fields.

We define an exchange that goes from one field to another as unilateral: it takes from one field to provide to another field.

III. Meta-Model in-depth description

The fields are made of different elements that share the same unit in their flow: these elements produce, consume or transform the same unit.

The energy field of the meta-model makes it possible to represent the fundamental element of microgrids, which is the energy flow or power flow. It represents all the energy exchanges within the microgrid and illustrates the amount of energy available [12]. Its unit is the Watt.

The information field of the meta-model represents all the data processed by the microgrid and the control of the microgrid. However, in a so-called "intelligent"; microgrid, this field becomes central for grid management, whether it be for the control or the monitoring and maintenance [13]. Its unit is the bit.

The financial field of the meta-model makes it possible to represent all the financial exchanges of the microgrid. As this field is often a limiting factor for the development of microgrids (especially in rural areas), it is essential to be able to represent it for its study [14]. Its unit is the local currency.

The social field, which is often forgotten or neglected in the study of microgrids, is fundamental to represent the microgrid in a

systemic way, thus understanding its functioning and state of health in depth. Its unit is social acceptance [15].

The fields presented above, based on isolated microgrids' meta-models, can be assembled into a single systemic meta-model. This assembly is done through what is called exchanges in this work. These exchanges are essential to understanding a microgrid as they may couple variables that are not necessarily studied together. There are twelve exchanges in the proposed systemic microgrid meta-model, as detailed in Table 1.

IV. Microgrid equilibrium

The notion of sustainability is fundamental in the design and operation of microgrids. It provides a clear vision and framework for developing a microgrid, which remains a somewhat fragile system [16]. Indeed, many microgrids have fallen into disrepair or function extremely poorly, particularly in rural areas with more limited resources, because certain limiting factors were not considered in the system's design [17]. The notion of systemic sustainability of a microgrid has already been partially addressed, but the presented meta-model provides a way to represent the grid's sustainability through the equilibrium of all the fields: the microgrid equilibrium.

With all its fields in excellent shape, this model will represent a microgrid that reaches energy sustainability, financial resilience, data value, and complete social acceptance. And overall, the microgrid will reach perennial operation.

The equilibrium of the entire microgrid is governed by the inner flows and the exchanges between the different fields. Dynamically speaking, these exchanges and flows can lead to failure or success. This section defines these two types of equilibrium and the means to evaluate them. To enter into what is called a virtuous circle, all fields must give as much as they receive. Since all microgrids are highly different in their architecture, sources, governance, population and many other factors, it is impossible to give a single solution for their

sustainability, but the meta-model allows to represent every microgrid in its entirety. For a short-term scale, the essential characteristic to identify the health level of the fields flows detailed in Table 2. A microgrid with an excellent operation in its fields will have increased resilience (at least for a short period of time) no matter the quality of the microgrid exchanges. Indeed, the high quality of its fields represents inertia and stability to the microgrid. However, for a more extended period of time, the exchanges of the microgrid will have a much more significant impact because if they are not efficient, they will gradually deplete the stocks of the different fields. Therefore, each exchange has associated indicators with being able to judge its good or bad functioning in Table 2.

To summarize this, it can be said that the flows of the fields represent the static sustainability of the microgrid and the exchanges represent the dynamic sustainability of the microgrid.

Table 2 details the notation for the flows and exchanges of the proposed diagnostic model. The ratings range from the worst possible scenario (rated as "--") to the best possible scenario (rated as "++"). The diagnostic tool that is presented uses this rating scale to rate each flow and exchange with a range of 1 to 4 according to the information collected on the microgrid to be diagnosed.

V. Use case

To benchmark the proposed meta-model, a study of six microgrids whose data is available in a United Nations report [18].

A colour code (red, orange, green, dark green) represents the quality of an exchange or a flow. These different indicators provide a general view of the sustainability of the microgrid but also the possibility to accurately anticipate weak points in the system and correct them before it is too late. The equation used for this calculation was:

$$Field_{score} = Mean (3 \cdot Field_{flow} + \sum Field_{Exchanges})$$

Where $Field_{score}$ is the total score of any given field, $Field_{flow}$ is the value given to the quality of the inner flow of the field and $Field_{Exchanges}$ is the score given to all the outward exchanges of a given field. The threefold importance factor was given to the flows to emphasize their inertia role in the fields.

The results are shown in Table 3. An average score and a variance are calculated for each microgrid on the bottom. The average and variance are calculated on the right-hand side for each type of exchange or flow. The rating used for the fluxes and exchanges varies from 1 for poor to 4 for excellent.

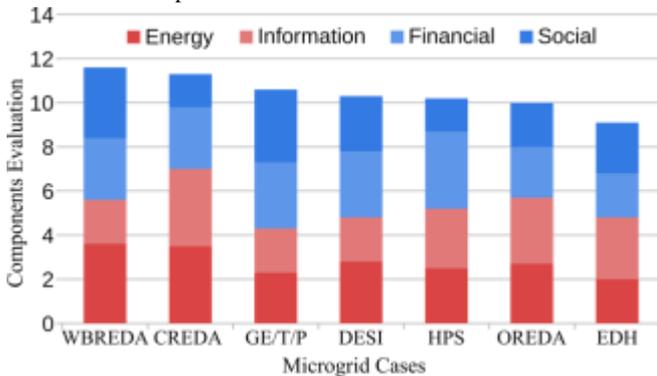


Figure 1. Microgrid use case evaluation

Figure 1 illustrates the results for each field. The blue fields are related to the community microgrid, and the red fields are related to the energy microgrid. The microgrids are lined from the highest score on the left to the lowest on the right.

Figure 2 compares the average and variance of the flows and exchanges for the seven study cases. It highlights how the social and information fields are the most neglected, with missing scores and no information available.

Following the UN report, the proposed diagnosis tool shows that microgrids that put resources into financial and social have a higher probability of success. This is the case for the first and third best-rated microgrids.

Figure 2 also shows that social-related exchanges are generally less accounted for in these study cases yielding a high variance.

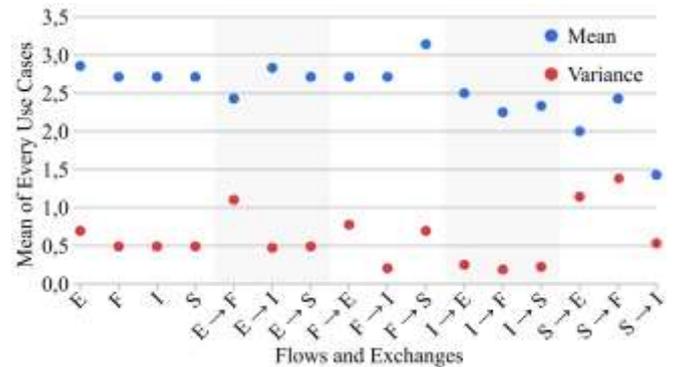


Figure 2. Microgrid flows and exchanges comparison

Moreover, we can also notice that the internal flows of the four fields all have a relatively good score, those being more visible in the functioning of a microgrid than the exchanges and are less often forgotten or neglected. On the other hand, the disparities are even more significant within the different exchanges, which shows the need for a comprehensible and systemic model for microgrids, particularly for rural electrification.

Indeed, although information flows are often well-considered and established, the exchanges that start from this domain seem to be very often neglected in the studied examples. Moreover, the social exchanges are very disparate depending on the case studies, supporting the fact that the social domain lacks consideration in the development of microgrids. These evaluations tend to support the conclusions of the UN report, which shows difficulties in the overall functioning of the microgrids as well as in the social consideration of the population, which can be compensated by information and social exchanges.

VI. Future Work

It is essential to understand that this diagnostic tool is still to be developed and refined. The various UN cases have shown the value of this microgrid vision by providing predictions similar to the report's conclusions. This approach centralizes all microgrid information into a multi-criteria assessment that is much simpler to understand while maintaining a high level of detail.

Work remains to be done in refining the way we model the content of the four fields to allow for the simulation of a microgrid model so that its evolution over time can be studied.

The detailed modelling of the elements of the fields still has to be formally defined. This would allow simulation of the model to study various expansion scenarios and bring a much more detailed evaluation of the microgrid operation.

The development of a meta-model with a lower level of abstraction could better represent and understand the exchanges and flows between the elements. Instead of making a global link between the fields, this meta-model would represent the flows and exchanges between the elements themselves. While keeping certain simplifications in the representation of the microgrid, this meta-model will allow, in addition to the diagnosis of the microgrid, a systemic simulation of its functioning.

The final aim would be to identify how expansion scenarios of different fields affect the long-term sustainability of a microgrid.

Table 2. Evaluation of the Different Flows and Exchanges.

To \ From	Energy	Information	Financial	Social
Energy	From energy sustainability with all objectives fulfilled (++) to no sustainability objectives validated (- -)	microgrid control is very accurate and stable (++) to microgrid control is poor and unstable (- -)	Funds are re-invested into power hardware with high maintenance (++) to no re-investment with poor maintenance (- -)	Community uses the power grid perfectly well (++) to community uses the power grid poorly (- -)
Information	Many precise measurements of the energy production are available (++) to no automated and imprecise measurement is available (- -)	From high data value and consummate control (++) to no objective validated for the data and control (- -)	Funds are re-invested into information hard-ware and software (++) to no funds are re-invested (- -)	The community fully respects the rules established for data collection (++) to community does not respect the rules at all (- -)
Financial	Energy enables productive uses (++) to energy has no productive uses (- -)	High quality data is available for planning and operation (++) to no data is available (- -)	From financial resilience (++) to no resiliency objectives validated (- -)	Payment collection is highly efficient (++) to payment collection is not reliable (- -)
Social	All energy needs of the community are satisfied (++) to not even the basic needs are satisfied (- -)	High quality data is available for the users to follow consumption (++) to no data is available (- -)	Funds are re-invested into the community (++) to no funds are re-invested into the community (- -)	From high social acceptance (++) complete rejection by the community (- -)

Table 3. Evaluation of the Different UN Use Cases

		CREDA	DESI	GE/T/P	EDH	OREDA	WBREDA	HPS	Mean	Variance
Internal Flows	Energy	4	3	2	2	3	4	2	2,86	0,69
	Financial	3	3	3	2	2	2	4	2,71	0,49
	Information	4	2	2	3	3	2	3	2,71	0,49
	Social	2	3	3	2	3	4	2	2,71	0,49
External Exchanges	Energy → Finance	3	4	3	1	1	3	2	2,43	1,10
	Energy → Information	4	2	3	2	3	N/A	3	2,83	0,47
	Energy → Social	2	2	2	3	3	3	4	2,71	0,49
	Finance → Energy	3	3	3	2	1	4	3	2,71	0,78
	Finance → Information	3	3	2	2	3	3	3	2,71	0,20
	Finance → Social	2	3	4	2	4	4	3	3,14	0,69
	Information → Energy	3	2	2	2	3	N/A	3	2,50	0,25
	Information → Finance	3	2	N/A	N/A	N/A	2	2	2,25	0,19
	Information → Social	3	2	N/A	N/A	N/A	N/A	2	2,33	0,22
	Social → Energy	1	2	4	2	1	3	1	2,00	1,14
Social → Finance	1	3	4	4	1	3	1	2,43	1,67	
Social → Information	1	1	3	2	1	1	1	1,43	0,53	
Results	Mean	2,63	2,50	2,86	2,21	2,29	2,92	2,44		
	Variance	1,05	0,53	0,59	0,49	1,14	0,91	0,93		

VII. Conclusion

This short paper reviewed the evaluation of different areas of microgrids to extract a more systemic meta-model. A meta-model was proposed to provide a clear view of all aspects of a microgrid to provide a diagnostic and planning tool for its sustainability.

Contrary to the visions that can be found in the literature, the representation of microgrids proposed in this short paper provides a complete tool that allows both to represent the microgrid in a systemic way, to be able to identify the different exchanges that exist between them but also to diagnose the overall health of the microgrid and to be able to estimate the future impacts of its internal problems. This is an essential vision to understand the different extensions of a microgrid.

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