Concerning the Sustainability of Smart Grids

A critical analysis of the sustainability of current Smart Grid models and on indicators of Smart Grid sustainability assessment

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***Abstract* — There is currently no generally accepted definition of Smart Grids, especially on what is expected to make them smart and how. On the other hand, the general assumption about Smart Grids implies the development of power networks toward more efficient, greener and sustainable systems. In this article, we present the intrinsic limitations of this view, showing how any aim for a future sustainable energy system will require analyses considering the multidimensional structure of the problem, including the integrated dynamics of different energy sources and carriers. The aim of this paper is to present the case for the development and conceptualization of a smarter and more comprehensive system known as Smart Energy Networks. We also put forward a set of indicators that we believe could aid in assessing the sustainability of smart grids and follow progress toward the development of a more sustainable energy regime.**

Keywords - Smart Energy Networks; Smart Grids; Sustainable Development; Sustainability Assessment; Energy Services.

I. INTRODUCTION

There is currently no accepted definition of Smart Grids (SGs). An argument can be made that, in many respects, this also reflects a lack of generally accepted understanding of what SGs should be, do or achieve. Any discussion on SGs, though, includes two commonly accepted premises: they represent the (on going) evolution of the power network and their development is driven by our – ever more pressing – needs for a more efficient, environmentally performing and sustainable energy system.

In recent years, the quest for energy efficiency and environmental performance has led to extending the boundaries of SGs and a broader concept of energy network has emerged [1],[2]. The expression Smart Energy Network (SEN) indicates a concept intended to go beyond the SG idea, where multiple energy carrier and their synergies can be considered. SENs are therefore defined by broader boundaries and they can be expected to provide a better systemic tool for the development of a more sustainable energy regime.

At the same time, analyses concerning the sustainability of SEN focus primarily on the environmental performance, and even more limited to center on the reduction of greenhouse gases (GHGs) emissions. The general expectation of lower GHG emissions is based on an increased use of Renewable Energy Sources (RES) and improved efficiency through owing to, and supported by, the technological development of the last few decades especially in the fields of Information and Communication Technology (ICT). On the other hand, to the best of our knowledge, no in-depth consideration concerning the overall system performance of SEN has been introduced or discussed, leading to, in our opinion, a number of significant misapprehensions concerning the expected results in terms of sustainability.

In this paper, we intend to address these issues, presenting how the concept of SG alone is intrinsically insufficient and a broader concept, such as the SEN is required to properly address the sustainability of the energy system. Furthermore, we intend to discuss the idea of sustainability within the framework of SGs and SENs. Far beyond the mere notion of environmental performance, the concept of sustainability in itself is a subject of intense research work; in this paper we intend to provide the readers with a set of elements to be considered in the quest for a more sustainable (and smarter) energy regime.

This manuscript, beside the introduction, develops on 3 sections. Section II introduces the concept of sustainability applied to the generally understood development of SGs, underlying, from different point of view, the limiting factors the concept of SG carries along in comparison with the more comprehensive concept of SENs. In Section III we introduce the paradigm shift required to overcome the presented limitations, suggesting what we believe to be the two key factors: addressing the multilayered and multidimensional character of sustainable energy system, and overcoming of the intrinsically limited nature of a quantitative understanding of the energy system. In Section IV we present a summary of our critical analysis of the generally accepted sustainable development of smart grids and our final conclusions.

II. ADDRESSING SUSTAINABILITY

Addressing the concept of sustainability, in our work we refer to the widely accepted definition of a process that "… meets the needs of the present without compromising the ability of future generations to meet their needs" [3]. Although often associated with environmental performance, and consequent separated references to economic or

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technological challenges and social acceptance/involvement, the concept of sustainability is based on what is referred to as the triple bottom line (TBL) (Figure 1). The TBL view indicates that companies ought to manage also their social and environmental capital in as much as they would manage their economic bottom line.

In this section, we discuss the currently generally accepted view of SG development from each of the mentioned sustainability dimensions.

A. The Environmental Case

The advantages and expectations concerning the environmental performance of SGs can, in most cases, be summarized in terms of significant reduction in GHG emissions through a wider use of RESs and improvements in terms of energy efficiency. We believe that, placed in these terms, both the goal and the means represent indeed fundamentally important factors for the development of a better energy regime, and yet they are an incomplete answer to the quest for a sustainable energy regime.

The reduction of GHGs is essential for combating global warming. On the other hand, it should be kept in mind that it is not the only element of concern in terms of environmental performance. Factors such as the competing uses of resources such as biomass and water, direct and indirect land-use impacts usually falls outside the spectrum of elements describable by using exclusively GHGs reduction based criteria.

Figure 1. The three pillars of sustainability [4].

Concerning the means through which we try to achieve our goals, it should be evident that the use of an increasing share of RES does not automatically imply an improved system performance toward sustainability. When it comes to evaluating the environmental performance on the use of RES, a good starting point is the fundamental limiting factors usually introduced in distinguishing renewable and non-renewable energy sources. Non-renewable energy sources are limited by the available stock: the progressive exhaustion of the stocks define the energy source availability usually in terms of financial viability and profitability. Renewable energy sources are defined by the flow: our limitations in tipping in these sources come, consequently, to be described in terms of limited capacity in "catching" these flows. If, in some cases, limitations are physical or technological, a limitation often overseen is defined by the limited resources we have at our disposal to bring to bear the means for "catching" the energy flow in the first place. Issues related to energy efficiency fall also under these limitations. In addition, the production and deployment of smart technologies massively rely on ICTs using a number of materials whose availability is given for granted. Scarcity of key component materials is a potential barrier to both large-scale deployment and reductions in technology cost. This is because many SG technologies (ICT and renewable energy) resort to critical metals. A raw material is labeled 'critical' when the risks of supply shortage and their impacts on the economy are higher compared with most of the other raw materials [5]. Critical materials important for low carbon energy generation and electronics share the same insufficiencies in their life cycles; low recycling rates and a high degree of dissipative losses, with a major share of the material being lost into other material flows [6]. Due to the rapid growth of SG technologies, end-of-life (EOL) management will become increasingly important. The role of recycling is negligible at the moment, but shall play an important role when recent and future installations will reach their EOL.

An important conclusion concerning the analysis of environmental implications for the development of a sustainable energy regime is that, also in the case of RES, we need to deal with stock limited resources. Since the development of a SG based system is expected to rely on these technologies, it is important to take these elements into considerations.

B. The Economic Case

In this paper we do not intend to produce an in depth discussion concerning the economy and economic mechanisms behind the development and deployment of SGs. It is, on the other hand, our intention to present few key points that we believe are generally missing and which are essential for sustainability.

Concerning the economic aspects of sustainability, this element is often understood in terms of financial profitability. Although an essential aspect of any system development, financial considerations should not entirely replace the economic ones (economic being here understood as the science that study the production, distribution and consumption of goods and services). Already the concept of sustainable use of non-renewable resources comes with some important economic consequences (e.g., access and use rate of mined resources) and, as mentioned in the previous section, it represents the determining factor for stock defined resources. On the other hand, even accepting the intrinsic limitations of a predominantly finance based approach to the problem, major concerns regarding possible contradictions in the development of a sustainable energy system arise. Simply put, the key issue resides in the maintenance of the core business model: as long as the customers pay for energy

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units (kilowatt-hours), the more are the kilowatt-hours sold, the better are the revenues supporting the growing energy business. The argument then can be made that there is little actual incentive to systematically reduce consumption or, in contradiction with a popular and generally supported understanding, energy efficiency does not – cannot – automatically translate in cheaper bills for the end-users at the end of the value chain.

C. The Social Case

The social dimension of SG development is often related, on one hand, with user response and interaction with a smarter power network, and, on the other hand, with concerns related to privacy and security with respect to a technology potentially very intrusive. We can argue that this is also a valid, important, and yet incomplete assessment of the social dimension related to SGs. A large use of RESs implies the distributed deployment of power generating units, access to resources often not necessarily accepted by the involved parties. Furthermore, privacy and security issues are often addressed with “end-of-pipe” solutions such as data protection, encryption, etc., while the efficient and effective system operation often relies on virtually unrestricted possibilities of access and control. A number of solutions concerning these issues have been presented, and they generally rely on the concentrated accumulation of data. Setting aside, for a moment, pure technological considerations and focusing on more technical aspects of this approach, a question should be asked on the direction we pursue for the design of the SGs system. The new system will be born from the synergic integration of the energy and the ICT networks, relying on, and supported by, an ever more decentralized power production and communication. Under the new paradigm, it should be questioned if physically decentralized power production system still relying on a centralized data management system can be still technically referred to as Smart Grid.

D. Sustainability Indicators

It is expected that long-term profitability of energy provision should go hand-in-hand with social justice and protecting the environment [7]. Indicators are needed to assess the environmental, economic and social sustainability of smart grids, to monitor trends in conditions over time, or to provide an early warning signal of change. It is widely recognized that some socio-economic indicators are related to environmental indicators (e.g., resource conservation) and that public acceptance depends on environmental impacts [8]. This manuscript recommends using a set of indicators under four categories, based on Dale *et al.* [9] and Global Reporting Initiative [7] to assess the sustainability of smart grids:

- Energy security and profitability
  - Security of supply
  - Net present value (NPV)
  - Energy price volatility
  - Trade volume
- Social acceptability
  - Energy quality
  - Data privacy and security
  - Transparency and compliance
  - Public opinion, stakeholder participation
- Social well-being
  - Employment
  - Impact on customer well-being
  - Access to energy
  - Diverse services
- Resource conservation
  - Depletion of non-renewable resources
  - Energy return on investment (EROI)
  - Land-use changes
  - (CO_2) emissions

This selection of indicators of SG sustainability is based on the availability of information about socioeconomic conditions for each category, on other efforts to identify sets of indicators, and on established criteria for selecting indicators. This set of 16 indicators is not as detailed or comprehensive as other approaches but, we argue, that it is more practical to apply. The indicators were selected based on being practical, unambiguous, resistant to bias, sensitive to changes, related to those changes, predictive, estimable with known variability, and sufficient when considered collectively [9].

III. PARADIGM SHIFT

The expression “paradigm shift”, a ubiquitous phrase often used to describe the radical changes SGs are expected to bring about on century old power system, finds its origins in the book *The Structure of Scientific Revolutions* by Thomas S. Kuhn [10]. In his book, Kuhn, a historian and philosopher of science, argued that science does not progress linearly but though a series of anomalies that challenge the existing theories and, after some time, generate a revolutionary change in thoughts, a paradigm shift. An often cited example of this process is the Copernican revolution vs. the Ptolemy’s view of the universe. The comparison between the Copernican and the SG revolutions is perhaps useful to underline the deep and radical system level re-thinking of the energy system required for a sustainability assessment. It is indeed the case that innovative solutions might appear more like an addition of system appendices, the equivalent of *epicycles* and *deferents* in the Ptolemaic system, rather than a radical, concept level, change of perspective.

Essentially, there are two key factors that need to be addressed: the intrinsic limitations of addressing the power system alone and the fundamentally quantitative understanding of the energy system.

A. A more comprehensive approach

As mentioned earlier, the expression Smart Energy Network refers to an information-based distributed system including a multilayered and multidimensional interaction

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of different energy carriers and vectors. The synergies among different forms of energy (end their network flows) allow for a more comprehensive theoretical framework upon which we could base our analyses.

A sustainability analysis focusing exclusively on SGs does not allow a proper and complete assessment of the entire energy system value chain. In particular, essential aspects of the energy production are amiss, as they do not directly contribute to the power system. Consequently, a *conditio sine qua non* is the consideration of a larger, more comprehensive system that would include the synergic flow of resources and energy. At the same time, broadening the system boundaries generally reduces the risk of externalities introduced in the previous section and calls for a general re-evaluation of system sustainability in the face of the new paradigm.

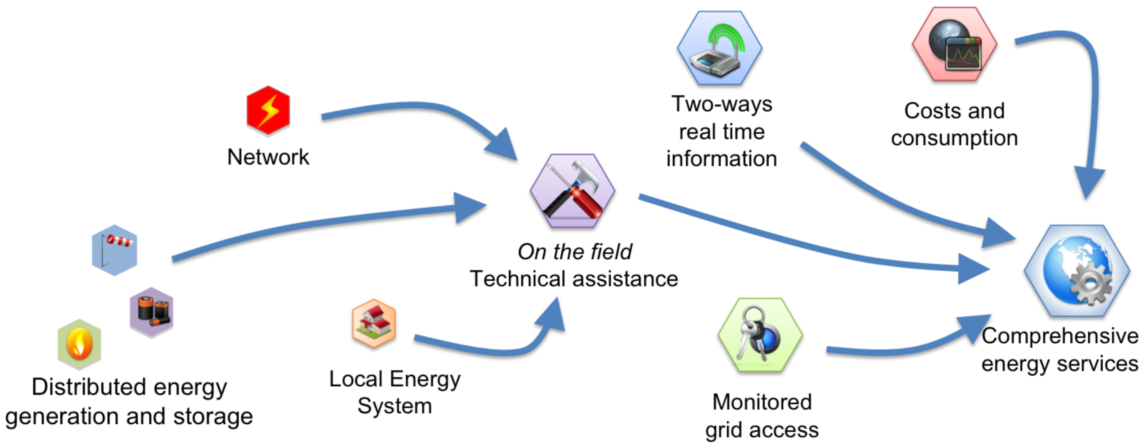

Figure 2. Indicative representation of the different elements required for an effective and comprehensive energy service to play a role in a smart grid based energy system.

B. *Energy Services*

In order to sustain a radical transformation of the future energy network, it is required for an important share of the future energy business to move from the production and commercialization of energy to the offering of comprehensive energy services (Figure 2). Customers' services would include, among others, monitored grid access, real-time information on costs and consumption, possibility to customize the service's profile and the possibility to sell small-scale renewable energy production in an open, transparent and easily accessible manner. These services rely primarily, but not exclusively, on efficient and effective data sharing and information extraction processes used by different operators to maintain a real-time overview of the network and feed back necessary, and valuable, information to end-users (e.g., energy consumption and price forecast). The other element energy services are to rely on is customized "on the field" technical assistance. This can potentially support the development of a more sustainable energy regime on two fronts. On one hand, end-users' living environments are expected to develop and grow in efficiency and complexity, requiring a number of dedicated and customized technical solutions and support services often currently not available on the market. This would potentially support the development of the system sustainability, especially for what concern the social dimension we described in section 2C. On the other hand, these services can support the development of an energy quality based systems rather than a material production ones. The key idea is to prevent moving the focus of the sustainability problem from the production of energy to the production of the materials required to produce energy, therefore avoiding the shortcomings we discussed in section 2B.

It is, notwithstanding, important for the new energy system to remove the commercialization of energy on a quantitative base as the primary economic driver. Based on our previous consideration, we can claim that any scenario built outside this premise is destined to present inevitable limitations, and any claim of sustainability can be put forward only by limiting the analyses to some specific element of the energy system (i.e., Smart Grids). Consequently any consideration of (un-)sustainability becomes, de facto, an externality.

Energy services are currently not widely available, or shared among a limited number of market players in a non-user-friendly way. Furthermore, each element of the network needs monitoring and assistance, they need to be combined at the local level and they need to be properly included in the common grids where their activity can be properly monitored in order to maintain the efficiency and the stability of the common networks. All these elements, even if, in most of the cases, are technically available, are not provided in a coordinated and viable fashion to the end-users. Other elements, especially for what concern the inclusion of the models considered in this work in the common grids, are currently not available. Apart from a number of administrative and political aspects, there are a number of technical obstacles that need to be overcome.

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IV. CONCLUSIONS

In this paper, we presented a critical analysis of the sustainability of smart grid development. We pointed out that, in terms of assessing the sustainability of smart grids, attention is often limited to environmental considerations only (such as CO2 emissions and the share of renewables), often ignoring entirely the economic and social dimensions of sustainability. More specifically, we showed that the concept of sustainability, in its sometimes underestimated complexity, comes, for what concern the future development of SGs, with two key elements of consideration: the first one is that the concept of SG is, in itself intrinsically inadequate for a proper sustainability evaluation as it represent a far too limited portion and, therefore, an incomplete representation of the energy system. The second point is that the economic driver of the future energy regime will have to oversee a transition from an energy based system to an energy service based system. Finally, we foresee that the social well-being impact of smart grids will be a key characteristic in European smart grid development efforts, with social acceptability providing a "make or break" feature, especially in terms of stakeholder participation, transparency and compliance.

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