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Challenges for a transition towards the smart grids

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Abstract. The recent evolution of the power and energy systems has been driven by a number of factors concerning network modernisation, energy efficiency improvements, growing attention to the environmental and social impact, higher diffusion of renewable energy generation, as well as guaranteeing system security and enabling new services and consumer participation. This paper presents an overview on the key challenges for the future energy systems, that will have to face with the energy trilemma including environmental and social sustainability, energy security and energy equity. The impact of the use of electricity in the energy systems is growing, calling for the assessment of future scenarios to understand the possibility of occurrence of critical conditions. The technical analyses can be supported by the definition of appropriate indicators, some of which are recalled in this paper. Emergent issues like transportation system electrification and system resilience have to be addressed in a holistic way. The various aspects of energy transition and energy integration require more interdisciplinary analyses merging competences from the technical, economic, and sociological fields.

Keywords: decarbonisation, distributed energy resources, energy integration, microgrids, resilience, sustainability.

1. Introduction

Despite some oscillations in the U.S. policies, there is a worldwide consensus on the objectives that must characterise the future use of the energy. According with the World Energy Council, these objectives can be synthesised in the *Energy trilemma*, with the basic keywords *environmental sustainability, energy security*, and *energy equity* [1].

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Sustainability is a term that everyone likes, but nobody is sure of what really it means and how can be measured. The usual definition, coming from a Commission of the United Nations, is "*a development that meets the needs of the present without compromising the ability of future generations to meet their own needs*" [2]. In some way, the basic inspiration takes into account the needs of the world's poor and the dangers that a sloppy use of the technology can put on an acceptable standard of living, from the point of view of social and economic acceptance and of preservation of the environment. A controversial aspect regards the use of the word '*development*', because it has created some worries in the developing countries, as if the developed countries were striking to put limitations on the economic growth using the lever of the pollution and environmental contamination.

Sustainability can be declined in social, economic and environmental versions, mutually linked with various degrees of priority, according with the stage of development locally attained [3]. Composite indicators are typically used to assess sustainability, considering different objectives and involving many individual indicators and data sets [4]. In the *Environmental Performance Index* (*EPI*), the two main groups of indicators objectives are *Environmental Health EH* (which rises with economic growth and prosperity) and *Ecosystem Vitality EV* (which comes under strain from industrialization and urbanization). In balancing the various dimensions of sustainability, the weights of the various indicators have been changed in time, i.e., in 2018 EH accounted for 60% and EV for 40% [5].

Security is a term that has to be contextualised, also making a clear distinction with respect to other terms, in particular with *reliability* (generally defined as "*The ability of a system to consistently perform its intended or required function or mission, on demand and without degradation or failure*" [6]). The North American Electric Reliability Corporation (NERC) is one of the few entities worldwide responsible for developing reliability standards for the interconnected bulk power system [7]. The NERC provides definitions of reliability by making a distinction among the two main concepts of *adequacy* ("*The ability of the electricity system to supply the aggregate electrical demand and energy requirements of the end-use customers at all times, taking into account scheduled and reasonably expected unscheduled outages of system elements.*"), and *operating reliability* ("*The ability of the bulk power system to withstand sudden disturbances, such as electric short circuits or the unanticipated loss of system elements from credible contingencies, while avoiding uncontrolled cascading blackouts or damage to equipment.*"). The NERC also provides a definition of *power system security*, as "*The ability of the electric system to withstand sudden disturbances such as electric short circuits or unanticipated loss of system elements*". When moving to *energy security*, the definition becomes more widely stated as "*Effective management of primary energy supply from domestic and external sources, reliability of energy infrastructure, and ability of energy providers to meet current and future demand*" [1]. These definitions are somehow classical for power and energy systems. Various security indices have been developed, for steady-state and transient conditions, also considering the uncertainty of the operating conditions and the risks due to the contingency occurrence. More recently, further concepts like *flexibility* and *resilience* have emerged, in order to address specific issues and situations not covered by the previous definitions. A discussion on these concepts is presented in Section 4 and Section 5.

Energy equity is the accessibility and affordability of energy supply across the population.

We could judge the energy policy of each country by considering their focused efforts to make progress in balancing the trilemma. Quantification of the balance obviously is not an easy task. Actually, it is performed using a set of indicators and data sets, with a methodology under constant review. It is interesting to list the top 2015 ten countries with the best balance: 1) Switzerland, 2) Sweden, 3) Norway, 4) United Kingdom, 5) Austria, 6) Denmark, 7) Canada, 8) France, 9) Finland, and 10) New Zealand.

In the view of the World Energy Council, the transition in the energy sector is driven by *decarbonisation* (with the growth of the energy supply from natural gas and renewable energy sources, together with the electrification of the mobility sector), *decentralisation* (with the availability of distributed energy resources – DER, composed of distributed generation, storage and demand-side resources), and *digitalisation* (with increased usage of information and communication technologies, and the diffusion of applications referring to the 'internet of things' for better integration of the distributed energy resources). Furthermore, the 2016 World Energy Council report [1] identifies five focus areas to achieve energy goals within a balanced energy trilemma: 1) transforming energy supply, 2) advancing energy access, 3) enabling consumer affordability, 4) improving energy efficiency and managing demand, and 5) decarbonising the energy sector.

Energy efficiency is a classical goal, whose characteristics are synthesised in the definition "*using less input of energy to produce the same service*" provided by the Lawrence Berkeley National Laboratory, and in the use of a number of indicators for its quantification. These indicators are generally expressed in two different ways:

1. For the assessment of a specific activity, the indicator used is the ratio between the energy consumption (kWh or other energy units) and the variable that represents the activity expressed in the appropriate units depending on the specific sector (e.g., tonnes, square metres, kilometres, number of employees, and so forth) [8].
2. For the comparison among the combined production of multiple energy vectors and the separate production of the same energy vectors from conventional systems, the dimensionless indicator used takes into account the savings in the fuel thermal content F from combined production with respect to the fuel thermal content F^{SP} in separate production (SP) of the same energy vectors from conventional systems. An example is the *Polygeneration Primary Energy Saving* (*PPES*) indicator [9] defined in (1), where X denotes the (known and fixed) useful energy output for a given type of energy among the ones produced in the poly-generation system (included in the set $\mathbf{X}$), and

η_X^{SP} is the conventional efficiency assumed for the production of the same energy X from separate production (as established by specific accepted standards or official documents)

$$PPES = \frac{F^{\mathrm{SP}} - F}{F^{\mathrm{SP}}} = 1 - \frac{F}{\sum_{x \in \mathrm{X}} \frac{X}{\eta_X^{\mathrm{SP}}}} \tag{1}$$

The acceptable conditions for combined productions correspond to $PPES > 0$.

Decarbonisation is a key issue appearing in all documents referring to the present and future evolution of the energy systems. The European Energy Roadmap 2050 [10] indicates four main decarbonisation routes for the energy sector – energy efficiency (with focus on nearly zero energy buildings and smart grids), renewable energy sources (RES), nuclear, and carbon capture and storage (CCS). The need for a urgent response to limit the global warming is today widely recognised, with unequivocal signals stating that unprecedented changes are in place for the global land and ocean surface temperature (+0.65÷1.06 °C in the period 1880-2012), reduction of snow and ice (with arctic sea-ice extent -3.5÷4.1% per decade in the period 1979-2012), and rise of the global mean sea level (+0.17÷0.21 m in the period 1901-2010) [11]. The European Energy Roadmap 2050 envisions an 80÷95% reduction of the emissions by 2050 from the 1990 level, and an almost total decarbonisation of the power sector by 2050, with relevant future role of electricity. Furthermore, the “Clean Energy for All Europeans” (or “Winter Package”) [12] has been issued in November 2016 by the European Commission as a package of legislative provisions aimed at facilitating the transition to a clean energy economy, based on the carbon dioxide reduction and the economic growth in Europe. The main goals concern energy efficiency, the global leadership in renewable energy sources, and the active role of the consumer in the electricity market.

Likewise the energy efficiency indicators for combined production of multiple energy vectors, the possible savings in the environmental impact are quantified by using the emission factor model [13]. This model is applicable to different types of environmental impacts, such as global warming, acidification and ozone depletion (Table 1). For each type of impact, there is a reference pollutant, and a multiplying factor that represents the equivalent effect of other pollutants causing the same impact. For example, global warming depends on a defined set of greenhouse gases, the reference pollutant is CO_2 and the global warming potential (*GWP*) for each greenhouse gas expresses how many kg of CO_2 are equivalent to 1 kg of that greenhouse gas [14]. For an equivalent pollutant p, the environmental savings are expressed by considering the equivalent mass $m_{p,eq}$ originated from combined production of a defined useful energy output X, with respect to the equivalent mass $m_{p,eq}^{\mathrm{SP}}$ in separate production of the same useful energy output from conventional systems. This framework leads to the definition of the *Polygeneration Pollutant Emission Reduction* (*PPER*) indicator [9], calculated by taking into account a conventional "environmental efficiency" in order to obtain a formulation similar to (1):

$$PPER = \frac{m_{p,eq}^{\mathrm{SP}} - m_{p,eq}}{m_{p,eq}^{\mathrm{SP}}} = 1 - \frac{F}{\sum_{x \in X} \frac{X}{\left(\eta_{p,eq}\right)_X^{\mathrm{SP}}}} \tag{2}$$

The acceptable conditions correspond to *PPER* > 0. Again, the separate production efficiencies have to be established by specific standards or official documents.

Table 1. Reference pollutants and multiplying factors for the equivalent pollutants.

Type of impact	*Reference pollutant*	*Multiplying factor*	*Reference condition*
Global warming	CO_2	Global warming potential (GWP)	$GWP_{\mathrm{CO_2}} = 1$
Acidification	SO_2	Acidification Potential (AP)	$AP_{\mathrm{SO_2}} = 1$
Ozone depletion	CCl_3F, also called R11	Ozone Depletion Potential (ODP)	$\mathrm{ODP}_{\mathrm{R11}} = 1$

2. The transformation of the energy supply

The evolution of the energy supply is based on some strategic pillars: increased use of renewables energy sources (RES), distributed generation, decarbonisation, electric penetration, electric mobility, distributed ownership and control.

Without doubt, RES will play a fundamental role in satisfying the energy needs. The European Union (EU) has fixed the target of at least 27% by 2030, from the estimated 16% in 2015. The more accredited forecast assigns to gas the major role as primary energy supply. Hence, it becomes compulsory for Europe to ensure new and diversified gas supply routes, from North to the South and vice versa. Still questionable is the role of nuclear energy that at present accounts for one third of EU electricity and two thirds of the carbon-free electricity, but it is not clear if and when the public opinion will allow a better framework, possibly after next generation systems.

As the energy related emissions account for almost 80% of the EU total greenhouse gas emissions, another EU target is the reduction of harmful emissions of 20% (and possibly 30%) by 2020 and of 80-95% by 2050. There is a large scepticism on the reachability of the targets without a drastic change in the general energy strategy.

Despite the impressive amounts in research, there are evident delays in technological progress and market investments. While changes are slow, challenges are increasing fast. Moreover, the actual business models show increasing weaknesses in allowing full exploitation of the present technologies and increasing barriers in allowing better paradigms for a complete and satisfying liberalisation. The actual panorama denotes serious gaps in delivery. While the wholesale prices are falling, retail prices are rising.

Technically the future of the electric European infrastructure can follow two paths, not necessarily alternative: reinforced transmission, and distributed generation.

2.1. Reinforced transmission

The biggest part of the electric and gas transmission is somehow obsolete and not adequate to provide the backbone for electricity and gas to flow where it is needed. However, to have a competitive energy market we must adopt a continental point of view. It is necessary to open the competition on a continental basis, avoiding national barriers. Primarily we have to build new electric highways and new gas ducts interconnecting the various European countries. Secondly, we must harmonise standards and rules.

In some ways, the energy infrastructure should follow the same path of the transportation and communications infrastructure. We do not have physical obstacles in driving a car from one country to another. Similarly, we do not have physical barriers in communicating across the world with phones or computers. For energy, we are still very far from reaching this kind of integration. For the electric infrastructure, a new continental and intercontinental high voltage (HV) structure would allow the transmission of relevant quantities of "green" energy across long distances, i.e. between Europe, Africa and Asia. This kind of solution is denoted as Global Energy Interconnection [15] and is aimed at the large-scale deployment of an ultra-high voltage (UHV) grid. That will open new possibilities of development for several underdeveloped countries, while offering new advantages to the more industrialised Europe.

In an historical period of confused political transitions, the attractiveness of continental and intercontinental networks poses several questions of security, due to the inherent weakness of large infrastructures extended across long distances and to the subsequent threats to national independence.

Things will be easier in the European framework, for historical reasons that allow more confidence in the solidity of the intra-European links and for the choice to proceed toward a full economical integration. Intercontinental connections can be mainly (or only) based on political visions and in any case their construction is a long-term process.

2.2. Distributed generation and microgrids

Distributed generation is undoubtedly the obvious evolution of the centralised approach. Among its principal advantages we can include an easier dissemination of the local renewable generation at competitive prices (i.e. photovoltaic, mini hydro, mini-wind) and a better global reliability (as the local service can survive to external distribution faults). A clear corollary is the microgrid solution. The U.S. Department of Energy Microgrid Exchange Group defines a microgrid as "*a group of interconnected loads and distributed energy resources with clearly defined* *electrical boundaries that act as a single controllable entity with respect to the grid and can connect and disconnect form the grid to enable it to operate in both grid-connected or island modes*" [16].

As long as the ownership of the microgrids is opened to private aggregations, their implications are not only technical end economic, but also social. We must insert this kind of evolution in a society that recognises new rights for the citizen of this century: the right of free energy, declined as the right to self-generation and self-consumption, the right to store energy and the right to sell and buy electricity in an open market with fair rules.

For each activity it is very important to assess the degree of *energy self-sufficiency ESS*, i.e., to what extent the local prosumed generation W_{pro} covers the local demand W_d (including local losses) [17]:

$$ESS = W_{pro} / W_d \tag{3}$$

More deeply, we can distinguish between the *ESS* and the degree of *energy self consumption ESC* that indicates which portion W_{pro} of the local energy generation W_{DG} is used to cover the local demand, while the excess of generation is injected in the external network:

$$ESC = W_{pro} / W_{DG} \tag{4}$$

In the illustrative example shown in Figure 1, with hourly local generation and demand patterns drawn for a period of one day, the total energy demand W_d = 112.3 kWh is the same for the three cases indicated. Conversely, for the generation the first plot is taken as the reference case with total energy generation W_{DG1} = 29.8 kWh while the second and third plots consider different generation patterns. Table 2 shows the *ESC* and *ESS* indicators for the three cases.

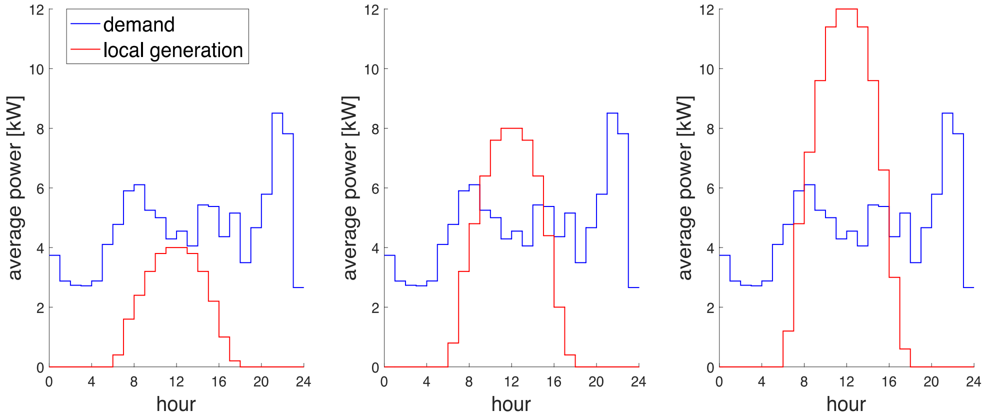

Fig. 1. Illustrative example for the calculation of self-consumption and self-sufficiency.

Table 2. Calculation of the energy self-consumption and self-sufficiency indicators for the illustrative example.

case	*Total demand* W_d [kWh]	*Local generation* W_{DG} [kWh]	*Generation excess* W_{out} [kWh]	*Prosumed energy* W_{pro} [kWh]	*Self-consumption* $ESC=100\cdot W_{pro}/W_{DG}$	*Self-sufficiency* $ESS = 100\cdot W_{pro}/W_d$
1	112.3	29.8	0	29.8	100%	26.5%
2	112.3	59.6	15.4	44.1	74.1%	39.4%
3	112.3	89.4	39.7	49.7	55.6%	44.2%

In the new scenarios of circular economy and diffused responsibilities, these indicators can be very useful in driving each activity toward energy self-sufficiency. For the smart cities, it has been already formalized the trend toward nearly Zero Energy Buildings (nZEB). But the trend is general and every energy efficiency program must take into account these kinds of indicators.

Distributed generation and the corollary microgrids must be seen also as a social opportunity to expand the freedom of the citizens, to create local sound jobs, to invigorate social consensus and to strengthening social links.

It is generally recognised that in the actual situation many consumers do not perceive that they are better off because of market opening and competition among different suppliers. The user suffers many disadvantages. There is a lack of adequate information on costs and consumptions. The markets are too much constrained and there are too many barriers. The choices are too narrow and there are too much obstacles to self-generation and consumption. While taxes, fixed costs and network charges are increasing, there is little convenience in introducing new technologies and participate actively to the transition.

Citizens appear to be unaware of their rights and reluctant to exercise them. Hence, the EU has launched a *New Deal for the consumers* [18], based on the need to put the citizens at the core of the transition. For a successful energy transition, the change should be consumer-centred, socially fair, job productive and environmentally friendly.

The legislative and normative framework must empower citizens and make them active participants in the market as investors and stakeholders. Individuals, but also collective energy organisations (aggregations, cooperatives, etc.) are fundamental to a successful energy transition. The typical passive user should evolve towards becoming an active user or prosumer, which participates in the energy market by producing renewable energy either on its own or collectively through cooperatives, social enterprises or private aggregations. Prosumers can contribute towards reaching the full potential of renewable generation, by maximising the development of photovoltaic, wind or other renewable energy projects in suitable areas, including on rooftops and lands area, which are not competitive with food production or with biodiversity conservation.

2.3. The important values

A new vision of the electric transition must review the important values and their priorities, to define a reasonable complex set of values as basis for guiding the transition. There are several important values of different type. We must consider social values (i.e., like social cohesion, fairness, skills, education, independence, responsibility, involvement, etc.), environment values (i.e., emissions, air quality, green attitude, etc.), economic values (growth, revenues, jobs, costs, etc.), and technical values (efficiency, automation, interfaces, etc.).

The choice of a fair complex set of values cannot be based only on economical or technical aspects. The choice must consider adequately the social and political values, considering the prospect of the future society affected by social tensions, risks of breakdown, and dangers for the environment.

The actual traditional set of values is strongly focused on stakeholders. On the other hand, Utilities rely on the volume sold (kWh), consequently locking the system into barriers against new entries. Utilities cannot really pursue a reduction on final demand and efficiency gains without undermining their core set of values.

For a fair and successful transition, it is wise to consider a better set of values, taking into account the benefits beyond the energy consumption, i.e., reduction of urgent network reinforcements, increased resilience, green attitude, etc.

Interests of the users and interests of the actual stakeholders can be conflicting. The correct equilibrium is not on win-win competition, but on cooperation, shared responsibilities, fair division of duties and rights. Competition induces more future competition. Cooperation induces more future cooperation. There is an evident flaw in the current business models, too unbalanced against the users. A new one appears attractive, if not necessary.

Consumers should have the right of free choice of aggregations independent of suppliers. It is necessary to support the local supply, allowing and promoting new organisational forms with legal ability to supply electricity to domestic and non-domestic consumers within a small-scale region, with fair access to the free market. Certainly, a new user-centric business model poses new risks, but also new opportunities. Under the generalised microgrid assumption, the utilities will experience reduction in sales and peak demand by a greater amount than in costs (revenue erosion effect). However, their future profit achievement should be based on more value-added services enabled or delivered.

The transition toward a new business model is certainly challenging and complicate. It requires a sound Value System Design (VSD), opening a new field for investigation. System changes proceed through gradually overcoming barriers that prohibit any new approach from consolidation in the sociotechnical terrain built for previous assumptions and stakeholders.

There are a lot of complicate interdependencies that one must take into account. A map of interdependencies occurring even for the simple case of installing solar rooftops on Finnish buildings is shown in [19]. In the general cases, the situation is much more complicated, calling for a strong political willingness to smooth barriers.

3. Smart grids and microgrid applications

3.1. Smart grids

The electric infrastructure that should enable the transition toward the new paradigms is commonly identified as *smart grid*. The practical technical implications of the smart grid concept regard the pervasive use of information, communication and automation in updating the electric network. The main drivers are the integration of renewables and the better exploitation of the available components. After more than ten years from the launch of the European Smart Grids Technology Platform [20], there have been many advances in the direction of modernising the grid by increasing the system automation, and in exploiting advanced information and communication technologies and more elaborated control functions in the electrical networks.

Today it is very difficult to construct new power plants or transmission lines, not only for problems of investments, but also for the social contrariety on visible technical components. Hence, we are forced to compensate somehow the reduction in the expansion possibilities with an increased use of the available components.

Then, smart grids lead to full automation of electric plants and power stations that should be controlled automatically both to reach the more convenient normal state and to react to contingencies through automatic reconfiguration.

The subsequent challenges are difficult, but still affordable with the current technologies. A big problem is the so-called cyber-security, to avoid errors and attacks through the information channels. However, there are also formidable algorithmic challenges, to take decisions under uncertainty and real time constraints. Particularly defying is the management of the uncontrolled distributed energy resources, due to the variability of the solar irradiance and of the wind speed and direction.

There are many technical issues concerning the development of distributed energy resources. Some indicators are summarised in [21].

A first example is illustrated here for the voltage deviation problem. In order to take into account the variation in time of the relevant variables, the indicators are calculated for a given period of observation T, partitioned into $t = 1,\dots,T$ time intervals with the same duration Δt (depending for example on the time step at which the measured data are available).

Let us consider an electrical distribution network with N nodes and B branches, denoting with $\boldsymbol{N}$ the set of the nodes and with $\boldsymbol{B}$ the set of the branches. The Total Energy Losses (*TEL*) indicator in the distribution network (excluding the transformers) in the period of observation is expressed in terms of the RMS current $I_{b,t}$ and of the branch resistance R_b, for each branch $b \in B$, as

$$TEL = \Delta t \sum_{t=1}^{T} \sum_{b \in B} R_b I_{b,t}^2 \, . \tag{5}$$

The indicator for voltage deviation can be defined in different ways, taking into account the voltage magnitude $V_{n,t}$ at node *n* and time *t*, and the admissible voltage range $(V_{n,\min}, V_{n,\max})$ for each node $n \in N$. One of the indicators is the Cumulative Voltage Deviation (*CVD*), calculated by summing up the deviations across space (nodes) and time:

$$CVD = CVD^{(+)} + CVD^{(-)} . \tag{6}$$

where

$$CVD^{(+)} = \sum_{t=1}^{T} \sum_{n \in N} \max \{ V_{t,n} - V_{n,\max}, 0 \}, \tag{7}$$

$$CVD^{(-)} = \sum_{t=1}^{T} \sum_{n \in N} \max \{ V_{n,\min} - V_{n,t}, 0 \}. \tag{8}$$

Alternatively, the indicator takes into account the Worst Voltage Deviation (*WVD*) with respect to the limits, across space end time, which can be defined by considering the positive and negative deviations separately:

$$WVD = WVD^{(+)} + WVD^{(-)} \tag{9}$$

where

$$WVD^{(+)} = \max_{t=1,\dots,T} \left\{ \max_{n \in N} \{ V_{n,t} - V_{n,\max}, 0 \} \right\}, \tag{10}$$

$$WVD^{(-)} = \max_{t=1,\dots,T} \left\{ \max_{n \in N} \{ V_{n,\max} - V_{n,t}, 0 \} \right\}. \tag{11}$$

Another indicator is the maximum branch loading (*MBL*) calculated as the maximum loading level of the branches across space and time, by using the branch current amplitude $I_{b,t}$ and the branch current limit $I_{b,\max}$:

$$MBL = \max_{t=1,\dots,T} \left\{ \max_{n \in N} \left\{ \frac{I_{b,t}}{I_{b,\max}} \right\} \right\}. \tag{12}$$

With the diffusion of the distributed energy resources, other indicators are gaining interest. One of these indicators is the curtailment of renewable energy sources (*RES*), namely, of the energy not produced (e.g., by wind or photovoltaic systems) when there is an excess of potential production with respect to what is needed to obtain the energy balance of the network, which would lead to congestion and/or risks for the system security. Let us denote with $w_{n,t}^{(RES)}$ the energy curtailed at node *n* and time step *t*. The RES energy curtailment $C_{tot}^{(RES)}$ in the whole period of observation is:

$$C_{tot}^{(RES)} = \sum_{t=1}^{T} \sum_{n \in N} w_{n,t}^{(RES)} \, . \tag{13}$$

The aforementioned indicators are only a small example of quantifying the possible effects of various technical challenges.

However, despite the technological advancements and the various indicators, it is still true that in critical situations the last word is always left to the operators. With the increasing amount of data and options, a very important aspect regards the interface between the field and the operators, especially when the operators have to operate urgently under the stress of incumbent contingencies.

In the actual state of the economy and of the social acceptance, it is clear that the construction of smart grids only with public investments would proceed very slowly. The only viable alternative is to attract private investments offering adequate advantages to the consumers. That brings into the general picture the microgrid approach.

3.2. Advantages of the microgrids

Social aspects apart, microgrids offers several important advantages. They make available and possibly convenient the availability of otherwise unavailable resources, generally with renewable energy. The typical examples are the roofs on the buildings. It is important to note that the electric consumption is only a small part of the general energy consumption in a building or in any structure.

The microgrid concept can be applied to integrated management of the various energies in the served zone (i.e. electricity, gas, water, heating, cooling, waste, etc.), allowing synergy and optimisation, with the possibility of easier planning and operation. Moreover, the microgrid is less vulnerable to contingencies, because in case of internal faults can draw energy from the external grid and in case of external faults can still provide energy with the internal resources.

The economic relations with the external resources can be simplified, with an integrated bill, and new opportunities may emerge for local jobs devoted to the operation and management of the microgrid.

Microgrids have proven their clear advantages in several situations, like isolated communities, underdeveloped contexts, industrial and scientific parks. However, there are also several technical points that need research and development of adequate industrial components.

The insertion of distributed resources in a conventional grid can raise the voltages at some nodes or can invert the flow of the currents in some lines. It follows that in general neither the microgrid nor the grid can take the opportune steps just looking at their terminals. It becomes necessary some kind of exchange of data and coordination between the controller of the microgrid and the controller of the grid, taking also into account that not all the renewable plants are and will be automatically controlled. The relevant concept is *hosting capacity*, that is, “the amount of electricity production that can be connected to the distribution network without endangering the voltage quality and reliability for other grid users” [22]. The related assessment is carried out in the present structure of the network, without considering the upgrade of the infrastructures.

Moreover, the renewable plants lack inertia, with danger for the frequency and voltage stability. In some way, this inertia can be reinserted through adequate electronic control of the conversions. Again, it becomes necessary some kind of coordination between local and distant control.

Finally, the behaviour of the microgrid and of the grid during contingencies (i.e. short-circuit) needs accurate planning and setting of the protections.

Improving the existing technologies can solve all these technical problems. The crucial point is another and regards the business model. The investments for connected microgrids are affordable only if the rules first allow the microgrids and secondly recognise adequately their contribution to the secure operation of the grid. There is some concern that the growth of the microgrids can imply the death of the grid, due to *grid defection*, that is, the trend with which the consumers could renounce to the connection to the grid [23]. However, in the current situation this is not a practical issue. In fact, the grid ensures better economic conditions, better reliability and greater global resilience (Section 5). Without the grid, the local consumer would be exposed to longer duration of the interruptions, and would need to buy and run local storage systems (still quite expensive) for guaranteeing reasonable characteristics of power supply. Due to its dimensions, the external grid is usually reliable and the quality of the service is stronger than for a smaller microgrid. The grid is and will be always necessary and convenient. But the synergy between microgrids and the grid can offer unprecedented advantages under several points of view, for example due to the presence of scattered local sources in the microgrid, which make the overall system less vulnerable with respect to the occurrence of a total blackout.

4. Demand side aspects, storage and electric mobility

4.1. Demand response and demand control

In the last decade, the demand side has been increasingly involved in the management of the energy systems through incentives or some degrees of participation to the electricity markets. Different levels of consumer participation, in ascending order of involvement of the consumer, are *load shedding* (in which the system operator cuts out a portion of the load in emergency conditions, without involving the consumer), *interruptible load management* (in which part of the load is cut by respecting specific conditions agreed with the consumer, and the consumer receives a remuneration), *real time pricing* (variation of the electricity rates during time), *demand response* (in which the consumer changes the electricity use voluntarily in response to price incentives), and *direct load control* (modification of the supply characteristics on the basis of the consumer's willingness to accept variations with respect to standard or predefined conditions).

Concerning *demand response*, the situation is evolving, however in Europe further regulatory improvements are needed in order to make these programmes effective. Various demand response services have been established in different countries, but the restricted consumer access to the demand response service providers is still a barrier to the effective operation of the market [24]. The opening of the balancing markets to the demand-side resources is in progress, but full opening of the wholesale market to demand-side resources is still expected, and the local system services are not yet commercially tradable in the European countries.

Automation and energy efficiency have their key points in the behaviour of the users. Automatic load control is a main driver in shaping generation and consumption for the best equilibrium between security, economy and comfort. Domotics and building automation are common words and are considered as the founding stone of any advanced smartness in grids and micrograds. A key aspect refers to demand *flexibility*, that is, the ability of shifting in time part of the demand, with many efforts from the conceptual and technological sides currently in place to define really flexible solutions and establish the *value* of demand flexibility in normal and emergency conditions, also taking into account the relations between costs and prices [25].

To convince the users to increase their willingness in spending money and accept the drawbacks of automation, not only we must provide evident advantages, but also we must offer easy interfaces and new ways of easy programming.

If we look at the technological evolution in several fields, we can derive some hints that the true revolution rarely comes from incumbent stakeholders if they work in a protected oligopoly. For obvious reasons the electrical infrastructure is a protected oligopoly. A suspect that the real breakthrough for the benefit of the users cannot come from the incumbent electric stakeholders but should come from the information and communication industry is quite reasonable.

What happened in the communication industry is instructing. The change in the way we use the telephone, did not come from the communication industries, but from outsiders, which manufactured system open to applications developed by a large multitude of brains. This kind of evolution is the result of opening the technological advances to the contribution of large quantities of young energies.

Breaking the central grid into smaller microgrids and opening the management and the operation in a free market could be the humus in which a huge amount of distributed intelligences can dramatically increase the smartness of the network. Conceptually some of these distributed intelligences could be potentially incorporated within an Internet of Things (IoT)-based framework, to enable the communication among objects. Possible IoT applications concern RES operation, demand response, electric vehicles, smart homes and fault detection. The communications could use different types of networks, from powerline carriers (PLC), WiFi, Bluetooth, and ZigBee, with 4G and in perspective 5G solutions. The major drawback of having many IoT units is the risk of being attacked by hackers. If the object considered for IoT handles information not crucial for its operation, the situation could not be critical. However, any object with operational capability, including smart meters and control systems, is critical for the applications in which the information is sent through the Internet.

4.2. Storage and electric mobility

There is still a missing leading actor in the rush toward the electric energy transition: the electrical energy storage, and particularly the batteries. The possibility of a convenient and economic electric storage is the real turning point in changing the speed of the transition. In the European Energy Roadmap to 2050 [10], the achievement of the targets in the different scenarios assessed has a common point in requiring *smart infrastructure including electrical storage*.

The development of viable storage solutions is a key factor for changing the paradigm of the energy system management from a just-in-time situation in which generation follows the load, to time-adjustable solutions in which the load (together with storage) follows the generation, also compensating the generation uncertainty and fluctuations. The presence of storage with its time-dependent constraints (state of charge and rate of energy provision) introduces a coupling-in-time in the system operation. This introduces the need of taking into account timing aspects in all the energy system studies. There are different objectives covered by different storage solutions, mainly aimed at improving the quality of the electrical service, providing flexibility to the energy system management, reducing the frequency variations, providing reserves at different time horizons, improving energy efficiency in multi-energy systems, and provide further solutions for the reinforcement of the energy systems during planning. The choice of the best mix of technologies has to take into account all these aspects [26].

Despite the investments in various kinds of batteries, today the hydro storage is still by far the most consistent solution, in terms of installed capacity and energy that can be provided. The research has proposed several new types of storage, either chemical or other types [27]. The advancements have been impressive. It is still extremely risky to forecast which technological solutions will gain the podium, but the investments and the urgency of a solution are increasing dramatically.

With available convenient batteries on large scale, all the panorama of grids and microgrids will change drastically. Also electric mobility will become a distributed reality. This is in line with the path to increase the penetration of the electricity as the prominent vector and is the condition to reach an acceptable decarbonisation.

The expected growth of electric mobility will have a considerable impact on the power systems, changing the load patterns and the network utilisation with the risk of overloads, and on the traffic flows, depending on the location of the charging points [28]. The sustainability of electric mobility solutions will depend on whether the electricity used to charge the vehicles will come from renewable energy (and associated storage). The environmental impact has to be studied in the life cycle assessment framework, including production, operation, and end of life of the vehicles and infrastructures.

However, it is still quite unrealistic to envision a full electric mobility in short time. With the most advanced battery solutions, we have achieved an energy density of 400 Wh/kg. In the next years the prospects can even double this ratio. However, for gas and petroleum the density reaches more than 12000 Wh/kg. Hence the path toward a less challenging comparison is still very long.

4.3. Energy integration – A matter of "X"

A key for the energy integration is the identification of common needs for services that can be supplied from different energy carriers. Then, it is necessary to construct the appropriate infrastructure for implementing the multiple supply and the interchanges among the energy carriers. A key point for integration is the *interoperability* of the infrastructures connecting the individual subsystems, together with the standardisation of the hardware (connectors) and of the communication protocols. These aspects are addressed by the documents prepared by entities such as the U.S. National Institute of Standards and Technology (NIST) [29].

The integration of different forms of energy is happening in different directions. The variety of the solutions has led to the conventional use of the letter "X" (with the meaning "everything") to generalise the energy carrier outputs from a given energy carrier input.

If the initial energy carrier is electricity, "Power-to-X" is typically used to represent the type of energy carrier in which the electricity produced is stored. Looking at the outputs, "X" can be an intermediate energy carrier (liquid or gas, leading to Power-to-Liquid or Power-to-Gas, respectively), or the final use (e.g., heat for Power-to-Heat, or the re-conversion of the intermediate energy carrier used as storage buffer into electricity for Power-to-Power solutions). In some cases the reference is to the service given, e.g., Power-to-Mobility. Likewise, the energy exchanges occurring in vehicular applications are denoted with the general term "Vehicle-to-X", leading to Vehicle-to-Grid (V2G), Vehicle-to-Home (V2H) or Vehicle-to-Load (V2L). Similar notations are used for the interactions with communication systems, e.g., Vehicle-to-Vehicle (V2V) and Vehicle-to-Infrastructure (V2I), also in combinations like V2V2I.

Energy integration has a big potential, due to the presence of a number of equipment carrying out energy conversions in a flexible way, such as electric heat pumps that may supply either heat or cooling as the output. The diffusion of systems enabling energy integration also reduces the need to reach a high level of electrification, since some services may be supplied in a "hybrid" mode from different energy sources. Specific models such as the ones provided by the *energy hubs* framework [30] enable the use of a black-box approach to build a representation of the entire system based on matrix representations of the topology and of the efficiency of the components. The key for enhancing the efficiency of the distributed multi-energy systems is to find out an optimal management of the internal resources, creating operational strategies different from the classical ones with on/off operation or electrical/thermal load following, also able to take benefits from the evolution in time of the energy prices [31].

5. System resilience

In the last years there has been a growing attention towards the concept of *resilience* (or *resiliency*). The term resilience has become more popular with the growing awareness that extreme meteorological conditions are becoming more frequent. Resilience expresses the ability of the system in tolerating extreme events while continuing to provide a service, even if reduced. The resilience to severe weather conditions has been included among the ten most important future trends of the smart grid [32]. The nature of the low probability and high impact phenomena referring to resilience is particular, thus requiring specific methods of analysis, different from the classical probability-based calculations. The major point is that resilience is different with respect to reliability. For reliability analysis, the focus is on long-duration outages occurring in large areas. Conversely, a study of resilience acknowledges that high-impact outages can occur, prepares to deal with them, tries to minimise the impact of the outages when they occur, figures out ways for quick service restoration, and learns from the experience to improve the performance in the future [33].

Obtaining an adequate resilience is the result of several actions, both on the grid and on the microgrid [34]. It implies modular components able to withstand extreme conditions, easily installable and interchangeable. It requires that the vital components should be easily reachable in protected environments and quickly replaceable. The design of the infrastructures in areas in which resilience issues do exist follows different principles with respect to the design in normal areas. Where resilience is a concern, the energy networks have to follow different and independent paths, to avoid (or at least limit) the simultaneous loss of all the networks. Also the control system should be able to detect in time the evolving faults in the system, allowing safe reconfiguration. Similarly, a high capacity of auto-diagnosis is needed for the components or part of the systems that are able to operate after the extreme event has occurred, helping the faster restoration of the supply during the emergency.

Dealing with resilience requires a holistic interdisciplinary approach, with the establishment of appropriate metrics based on quantitative indicators, the definition of adaptation strategies, and an extended regulatory and policy framework incorporating aspects belonging to different fields (power engineering, civil engineering, information and communication) [35]. The analysis of the restoration strategies has to take into account also a number of behavioural and sociological aspects, identifying the positive and negative reactions of the people subject to the consequences of catastrophic events.

Conclusions

This paper has provided an overview of the main aspects referring to the current evolution of the smart grids, pointing out the challenges and the directions to reach better solutions for the future energy systems. From a global perspective, the possible solutions have to be found by considering the different points forming the energy trilemma. In practice, the current evolution of the technologies and of the energy management systems is leading to the transition to a more electrical system. The electrical infrastructure is evolving both at the electric highways macro-scale level, and closer to the final users at the microgrid level. The final users have to be involved to a larger extent on energy management, also removing some barriers to their effective involvement. The decarbonisation objectives aim at increasing the energy production from renewable sources. The electrification of the transportations has a major impact on the need to increase the capacity of delivering power through the distribution networks. Energy efficiency improvements can be obtained from combined production of multiple energy vectors. The integration and coordination of electrical and thermal system also offers opportunities for increasing the flexibility in the use of the resources, especially when using different energy carriers can provide the same service.

The current activity is directed to the quantification of the opportunities to reach better integration among the energy systems, also taking into account the value of the flexibility in the use of the resources and in the provision of reserve services in case of need and in emergency conditions. The risks of physical or cyber attacks are among the major concerns for the development and operation of the future systems. A possible warning on the consequences of energy system integration is that the added complexity could introduce cyber-security vulnerabilities. Finally, the increasing attention towards mitigating the effects of extreme weather events on the population and on the technological systems requires the set up and the progress of an interdisciplinary culture of resilience.

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