Beyond smart grids – The need of intelligent energy networks for a higher global efficiency through energy vectors integration

Fabio Orecchini, Adriano Santiangeli*

DME – Department of Mechanics and Energy, “Guglielmo Marconi” University, Via Virgilio 8, 00193 Rome, Italy

ARTICLE INFO

Article history:
Received 20 January 2011
Accepted 28 January 2011
Available online 3 March 2011

Keywords:
Intelligent energy networks
Smart grids
Energy vectors
Renewable energy
Distributed generation
V2G vehicle-to-grid

ABSTRACT

From the energy point of view, the season we have been living more and more seems the era of sources diversification. The most correct scenario for a sustainable energy future foresees no predominance of one source over the others in any area of the world but a proper energy mix, based on locally available resources and needs.

The concept and role of energy vectors is key: "(an energy vector) allows transfer, in space and time, a given quantity of energy, hence making it available for use distantly in time and space from the point of availability of the original source". Therefore, a scenario that gives full scope for the ES to be immune from the characteristics of non-sustainable resource consumption and waste production, the system itself must shift the focus from resources to vectors (mainly electricity, hydrogen, heat).

Smart grids have been largely indicate, in this context, as an answer for their characteristic “needful design” to move from the “old” grids (unidirectional power flows) to “new” bi-directional electricity networks. This is not enough: the real need is for an intelligent management of a complete set of energy sources and vectors, as electricity, heat, hydrogen, bio and non-biofuels, that requires a clear shift that goes beyond smart grids and looks at Intelligent Energy Networks.

Copyright © 2011, Hydrogen Energy Publications, LLC. Published by Elsevier Ltd. All rights reserved.

1. Energy systems scenario

The main current and expected energy problems are related to two main topics:

- Securing energy supply;
- Reducing environmental impact.

To solve these two kinds of problems there is a dramatic need of change in terms of resources, that have to be abundant, available and diversified, and emissions reduction in any phase of the energy chain, from resource to conversion systems, storage and transportation and final use (Fig. 1 shows an example of an energy system design with renewable energy sources).

These objectives can be attained the energy system (ES) is structured to be able to use locally available and mostly renewable resources, and to produce an useful effect with either low, or zero emission level.

The “old” grids and energy networks have been designed for large centralised power plants and little distributed generation (DG), with a particular geographical distribution of...
resources, to manage unidirectional power flows and with a centralised dispatch and control units and with no consumer participation. Smart grids are able to work with bi-directional power flows that allow: the management of DG, the management of renewable energy sources (intermittent), the demand and storage management optimisation, a multi-lateral participation in the real-time balance between energy supply and energy demand.

In this way we can think of electrical grids operating in a system that is able to make coexist concentrated and distributed power plants. The system assumed in order to manage distributed generation, integrating them with those of concentrated generation, is to think about managing their aggregate to form a sort of micro-grids or ‘virtual power plants’. In fact, the growing of low and zero carbon generation technologies, significantly increases the weight of DG in the calculation of the total electricity production plants stock. This means having more customer-centric electrical grids that will then be managed in an intelligent way by imposing the need to operate in a planned and shared way at European level on the structure and control grids.

2. Structuring the energy system, from the energy cycle to appropriate energy vectors

The energy cycle starts from the so-called primary (or natural) forms of energy, uses the energy flows (which include transformation and conversion processes from primary energy), and reaches the most appropriate form of energy to meet end use, until achieving the useful effect. Obviously, the energy cycle – in its nowadays commonly used form – entails an interaction with the environment as well as the production of waste and pollutants. The ES must allow transformation and conversion processes and flows, where energy (primary or not) is processed until reaching the end uses and producing the useful effect. The energy system is therefore satisfactory when it is able to guarantee the right quantity and form of energy in the right moment and at the place of need [1].

The integration of appropriate energy vectors allows to transfer, in space and time, a given quantity of energy, hence making it available for use distantly in time and space from the point of availability of the original source.

The energy cycle can be open or closed: an open cycle starts from a state of environmental balance and ends with a condition of environmental imbalance. This cycle “consumes” resources and “produces” waste. The cycle of an energy resource can be defined as “closed” when it does not “consume” resources that cannot be re-formed on the Earth in due time, and when it can theoretically reduce to zero the impact on the environment (Fig. 2), in terms of both terrestrial resource consumption and waste formation [2]. The energy amount “paid” to produce the eventually needed energy vector is amply compensated by the renewability of the resource and its (assumed) endlessness of availability for humankind.

In this context, the distributed generation assumes a fundamental role to the penetration and diffusion of closed cycles based on renewable energy sources and an intelligent energy network represents the only mean to manage the entire system in an intelligent, effective, efficient and environmental
3. Distributed generation

Distributed generation has an increasingly important role in the energy network of the future. This is mainly due to the increasing availability of technologies used in small sizes, which, in a scenario of liberalised energy market is decisive, and the rising attention to the exploitation of renewable energy sources [6], which may allow the earth to free itself from some problems linked to non-renewable sources: exhaustibility, emissions, perceived dangerousness.

The distributed generation of electric power is based on the use of small-size generators that operate close to end users and with a power ranging from a few kW to some MW. This small size of distributed generation plants does not entail the need for high-medium voltage distribution networks and, at the same time, allows to use low-voltage for local connections. Furthermore, their progressive and non-traumatic introduction is favoured, both in those cases in which a production structure is missing, and when replacing the existing networks is considered as suitable or convenient [7]. The main specific requirements of DG, include the plant-engineering modularity, the reduced management and maintenance needs and the reduced emissions. These requirements allow to have installation costs almost independent from the size (we can scale power according to users’ needs), no frequent maintenance with specific professional skills, strict limits to emissions (due to installations at users, including in towns).

To this day the DG solution has been used as stand-alone units: micro-generators in DG have allowed the use of a potentially unlimited range of energy sources and, in any case, much wider than the one of central systems, which mainly operate with traditional fossil fuels. In particular, the small scale entails flexibility in the choice of energy sources, depending on local availability, geographic characteristics, as well as on the technological and economic conditions of users. Established fact, the low spreading of distributed generation, and the subsequent and continued marginality of the relevant technologies, limit the field of usable sources. Among fossil sources, natural gas, oil and reforming hydrogen have the lead. Among renewable sources, thermal and photovoltaic sources prevail. The reference to hydrogen implies its use both in a long-term perspective, as a main energy vector in fuel cells, and in a short/medium-term perspective as a component of fuel mixtures (i.e. hydrogen–methane mixtures) in heat engines [8,9].

4. From concentrated production to distributed production

The present organisation of the energy system at a national level is mainly based on the production concentrated in very few large plants, located far from users, and on the transportation and distribution of the energy produced to end users. This organisation, therefore, does not only concern production plants, but also the other infrastructures (the distribution grid) that represent the energy system as a whole. A passage from concentrated to distributed production, therefore, cannot only concern energy production technologies, but also all the components of the energy system, that is to say the infrastructures for energy wheeling, vectors themselves (since a distributed generation system shall provide for the use and therefore the supply of hydrogen) up to the technologies for end use.

The present distribution grid was essentially conceived and organised to transport energy towards one direction only (from production centres to users), namely it is unidirectional, passive, and able to absorb power only from higher voltage grids. Therefore, it is limitedly suitable for a bi-directional system in which distributed production has a particular relevance from the quantitative viewpoint. In 2005, in fact, in order to face the problems linked to an electric grid system no more unidirectional, the SmartGrids European Technology Platform (ETP) was set up. “The aim of the SmartGrids...
European Technology Platform for Electricity Networks was to formulate and promote a vision for the development of Europe’s electricity networks looking towards 2020 and beyond [10].

Compared to traditional electric grids, characterised by large plants with a technology consolidated over decades, centralised control, and optimal management at a regional level, Smart Grids exploit at best the advantages offered by the digital era (Table 1), but for this purpose they have to be:

- **Flexible**: Fulfilling customers’ needs whilst responding to the changes and challenges ahead;
- **Accessible**: Granting connection access to all network users, particularly for RES and high efficiency local generation with zero or low carbon emissions;
- **Reliable**: Assuring and improving security and quality of supply, consistent with the digital era demands;
- **Cost-effective**: Providing the best value through innovation, efficient energy management and ‘level playing field’ competition and regulation.

In such a project, a smart grid scheme (Fig. 3) must envisage that:

- The system operation will be shared between central and distributed generators.
- The control of distributed generators might be aggregated to form micro-grids or ‘virtual’ power plants to facilitate their integration both in the physical system and in the market.

### Table 1 — Today’s Grids and Smart Grids-ETP.

<table>
<thead>
<tr>
<th>TODAY’S GRIDS</th>
<th>SMARTGRIDS</th>
</tr>
</thead>
<tbody>
<tr>
<td>large centralized generation</td>
<td>they accommodate bi-directional power flows</td>
</tr>
<tr>
<td>geographical distribution of generation resources</td>
<td>they allow:</td>
</tr>
<tr>
<td>power flow in one direction from the power stations</td>
<td>distributed generation management</td>
</tr>
<tr>
<td>dispatching of power and network control → centralized facilities (controlling several regions from one place)</td>
<td>renewable energy resources management</td>
</tr>
<tr>
<td>There is little or no consumer participation and no end-to-end communications</td>
<td>optimization of DSM (demand side management)</td>
</tr>
<tr>
<td></td>
<td>optimization of Storage management</td>
</tr>
</tbody>
</table>

| Coordination of local energy management and full integration of DG and RES with large-scale central power generation |

5. **From fuel stations for vehicles to V2G (vehicle to grid network)**

In a future energy scenario, the automobiles and other vehicles will be more important. To date, the word vehicle was substantially associated with the term consumption, in terms of fuel and space. When we drive a vehicle, fossil fuels are burned with very low efficiency, and when the vehicle is stopped, the occupation of space is even “passive”. In the near future, the process of vehicle electrification [11] will bring on one hand to the change of the energy vector (from fossil fuel derivatives, to a mix of vectors, as bio and non-biofuels, electricity, hydrogen), on the other hand a new role of the vehicle as an electricity (or energy vector) storage and distribution

![Fig. 3 — European Smart Grids Technology Platform: Electricity Networks of the Future.](image-url)
actor of system. When the vehicle is not driven, it can switch from passive to active its energy role, by being connected to the power grid and operate in a bi-directional way.

The electric-drive vehicles, whether BEV (Battery Electric Vehicle), FCEV (Fuel Cells Electric Vehicle), or PHEV (Plug-in Hybrid Vehicle), change their function in the energy system for mobility. So these kind of vehicles could be connected to the grid not only to be recharged, filling-up the traction batteries but also to give energy back to the grid, interfacing their power electronics to the smart grid. The term used when connections are added to allow this electricity to flow from cars to grid, is “vehicle to grid” power, or V2G [12].

It is clear that the implementation of a V2G system should provide a standardised plug-in charging system, an infrastructure project planning and planning the timing of the flows of energy demand. The Fig. 4 is an example (Source: Micro-Climates EV) of possible types of charging systems grid connected (from the fast charge station to the smart home system and charging station, charging from the parking lot to the street charging service).

The plug-in electric vehicles can be considered as an opportunity and not as a limitation for the grid. A plug-in electric vehicle is, by definition, not just a mean used for moving people or goods, but it is a real energy storage system. It is known that the average time when the vehicles are parked or unused is far larger than that of their use. The potential gains are many. The load curve of the network could be flattened with its attendant benefits on performance of appliances that will be working in a range of much smaller operation than at present and therefore less likely to malfunction and unplanned maintenance. In view of renewable energy, however, the vehicles could accumulate the energy produced surplus and give it back to the grid at times of greatest energy demand. Vehicle owners may receive certain benefits.

Another step beyond the V2G, could be the inclusion in the bi-directional flow energy management also the other two vectors: hydrogen and heat. The first one stored in the vehicle tank (hydrogen pipeline in an hydrogen network) and the second one produced when vehicle is running (district heating and CHP vehicle systems in an heating and electricity network). When a parked FCEV is running, it can produce electricity as well as heat, both usable in a distributed generation system.

6. From smart grids to intelligent energy networks

The IEN, Intelligent Energy Network, is an integrated network of multiple energy vectors managed in an intelligent way. The IEN is to be capable, thanks to a continuous monitoring and analysis of the energy needs in quantity, quality and type, of managing energy vectors production and storage points available in a pre-defined section of the network (IEN cell) to produce, transport/store, and supply the right mix of energy vectors to meet the demand (Fig. 5). The target of any cell, as well as the one of the entire IEN is the achievement of the highest instantaneous efficiency and lowest emission level. A theoretical “static” solution, with highest performance and lowest emissions, could not be adopted instantaneously. It
depends on what happens in the network at that time, on the energetic availability and priorities. A neuro-fuzzy looks as the best up-to-date logic to manage the process, where any experience in a situation occurred, will cause the system to evolve with an increasingly high degree of efficiency and effectiveness in the energy vectors production, storage and supply mix.

The management of an IEN seems to be more complex than the Smart Grid’s one. An IEN works not only on a bi-directional flow of the single electricity energy vector, but also on bi-directional of some other energy vectors (heat, Hydrogen, synfuels, others). Though the parallelism: “the more numerous are the vectors, the more complex is the system to be managed” appears as evident, it is not given that a real comparison between the entire ES in the case of SGs, and the entire ES in the case of IENs will indicate a greater complexity for the latter.

The SG system seems of easier design and management because it considers only one part of the ES, related to production and distribution of electricity. The fluxes and

Fig. 5 – IEN: IEN cell, storage and production points, final use points: dashed line indicates monitoring, analysis and operating system; thick line indicates different energy vectors.

Fig. 6 – Organisation chart as an Intelligent Energy Network.
processes of energy vectors to be produced, stored and moved to allow such production are not considered by the SG itself, but they are part of the social, economical, production system that incorporates the SG. If the comparison is enlarged to the two complete systems: one incorporating the SG without intelligently managing the sources, technologies and vectors out of it, the other as an IEN, then the complexity balance is more likely to indicate an advantage in simplicity for the IEN compared to the SG + n different and non-interrelated energy systems.

It is evident that distributed production does not necessarily eliminate large energy production plants. The Fig. 6 shows a possible organisation of an IEN cell, based on distributed generation integration with centralised one.

In an organisation as an IEN, thanks to an “intelligent” use of a different mix of energy vectors (giving priority to zero emission usability), like electricity, heat and hydrogen, the coverage of the energy needs of single users will no longer be entirely met by the national network but rather partly covered by the integrated plants that produce energy directly for users (micro energy networks in distributed generation) and partly by the national network. Therefore, the energy taken from the network by a single user will partly come from the national grid (powered by large concentrated production plants), partly from medium-sized local plants, and partly from other users at the city and/or district level that during the production phase had no consumption needs (Fig. 7). This type of system therefore, will have a series of energy production and storage micro-stations locally. In this way, we want to remember what we said earlier on vehicles: stationary vehicles are usable energetic storage systems. All this, mandatory managed by a series of intelligent energy networks linked to national and trans-national level.

Furthermore, it is to be underlined that the use of distributed generation allows to more often employ cogeneration (even including CHP vehicle systems), which is very efficient; this is clearly impossible in the case of concentrated generation, since heat transportation for very long distances is not feasible.

7. Conclusions

A cornerstone to the construction of a trans-national energy network has been laid in Europe, with the establishment of the European Technology Platform Smart Grids (SGs) with a vision and strategy for Europe’s electricity networks of the future.

The Intelligent Energy Networks (IENs) go beyond SGs by integrating a network of different energy vectors managed in an intelligent way, instead of the electricity alone – as in the SGs. The IEN continuously monitors the energy needs in quantity, quality and type, and consequently runs the different energy vectors production and storage points available. The target of any cell, as well as the one of the entire IEN is the achievement of the highest instantaneous efficiency and lowest emission level. While an SG seems less complex than an IEN, when the comparison analysis is made at a compatible level – by figuring the entire energy system – it is evident that SGs cannot work properly if an intelligent management of the complete energy System is not made: sources, technologies and vectors.

The concept of IENs is an effective way to highlight the importance of renewable energy sources, and new energy vectors integration in the ES, as hydrogen, that can be produced from different renewable and non-renewable resources, effectively stored at various levels, and used for an on-demand, zero emission instant production of electricity and heat.

Acknowledgements

The authors wish to thank their scientific mentor professor Vincenzo Naso, director of CIRPS.

References


Tomić Jasna, Kemptona Wüllett. Using fleets of electric-drive vehicles for grid support. J Power Sources 1 June 2007;168(2): 459–68. Published by Elsevier B.V.