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Hydrogen to link heat and electricity in the transition towards future Smart Energy Systems

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ABSTRACT

Nowadays, two fundamental issues are related to the Energy transition towards Future Smart Energy Systems: the design of new high efficiency technological appliances and the use of new Eco-fuels. The crucial challenge is to integrate the increasing share of intermittent RES (Renewable Energy Sources) in National energy mix. Above all, linking both heat and electricity production is the key strategy to face this challenge at urban, regional and national scale. Power-To-Gas application by means of Renewable Hydrogen (H_2) production would be the viable solution due to H_2 has a double application: as a fuel for combustion or chemical conversion as well as an energy storage medium for RES mismatch compensation. In this paper four different H_2-technologies were considered: Hydrogen enriched Natural Gas (H2NG), MHHP (Metal Hydride Heat Pump), GHP (Gas-driven Heat Pump) and SCH4 (Synthetic Methane). An aggregated energy system model was built to assess H_2 contribution in PES (primary energy saving). When RES share ranges from 25% to 50%, using H_2 for heating purposes avoids the low round trip efficiency of its deferred electricity purpose. If transport excluded, there are no meaningful gains from H_2Ts systems but, they allow to green NG end-uses and decarbonize heating, especially, where NG-Grid is widespread.

1. The energy transition context

The mid-term and long-run climate change-driven roadmaps are promoting the use of renewables as low or zero carbon energy sources. The goal of those strategic plans is to decarbonize the energy systems to avoid the critical CO_2 concentration and its consequent greenhouse effect of increasing the world's temperature of 2 °C [1]. The integration of renewables has a double effect: the substitution of fossil fuels to reduce primary energy consumption and to facilitate energy security. Whereas, the increasing of RES (Renewable Energy Sources) share in national energy mixes affects negatively the Grid, in terms of efficiency due to running the existing fossil fuel power plants at partial load; the electric cables stress owing to the change in time response; and in terms of energy mix composition due to the shock on the market provided by the feed-in-tariff incentive schemes and due to the different RES priority of dispatch mainly driven by national policies rather than their conversion efficiency. Furthermore, a decreasing of energy price in peak hours and the strong reduction of incentive schemes subsides together with the introduction of the Capacity Payment mechanism, which substantially refunds the fossil fuel investment [2] and the repowering of existing power plants made since 1990's, imply system balancing issues to be solved. As shown in Fig. 1, the average National Grid efficiency raised of 3.5%. In the first decade of 2000, many drops in value corresponded to the starting of new RES plants, e.g. in 2006 and 2009. While, in 2011 a global efficiency increase is noticeable due to the economic crisis which entailed a cut in subsides to new RES installations.

A similar trend is expected until 2030. The main reasons are the strong fluctuations associated to more and more new renewable energy production to achieve the Roadmap 2030 goals and the shift of fossil fuel-based plants from baseload supplier to RES backup option. Instead of concentrating the economic efforts in building new large-scale efficient power plants, in the future forced to work in off-design conditions, Distributed Generation could offer an efficient solution such as the SchwarmEnergie [4]. This latter means that energy is generated whenever it is needed. So, it is possible to

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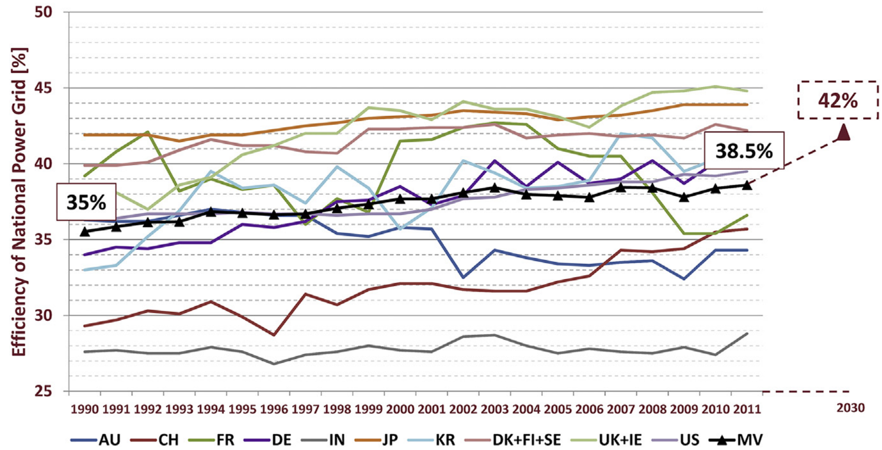

Fig. 1. Historical series of Grid Efficiency values from 1990 to 2011. Source: Authors' elaboration from Ref. [3].

switch-on only the needed small-scale CHP plants at their rated load as well as their best efficiency.

Above all, OECD Countries have already more power than needed and the new renewable-based energy production entails the excess electricity issue. As previously demonstrated by Mathiesen et al. [5], converting excess electricity to other energy forms such as fuels or chemical storage for electricity purposes, i.e. for putting it back on the electricity grid, should be avoided as option to balance renewables fluctuations due to their low round trip efficiency. As a matter of fact, electrolysers represent a good solution for balancing the penetration of electrical renewables in energy systems as the main part of synthetic fuels production. That cycle provides many advantages, mainly by connecting different energy sectors, by integrating a higher amount of renewable electricity and by overcoming land-use issues, typically associated to bioenergy supply chain [6,7]. Furthermore, the conversion of renewable energy overcapacity could mitigate the energy dependence, still a geopolitical issue. Among those measures, hydrogen produced by electrolysers is the best solution to manage excess electricity and to resolve problems in electrical systems [8]. Once started the adoption of balancing solutions for the Grid towards a Smart Electricity, another key point is the interaction with the heating sector. A first attempt is the Power-to-Heat solution by means of Heat Pumps, where they represent a more efficient solution owing to their COP but, they work at lower input–output temperature (e.g. hot water at 55 °C). Indeed, the HPs use in replacing conventional systems in the transition phase requires several adjustments: firstly, a different temperature asks for a new larger size of the end-users terminals, secondly, a new higher electrical load to the local electricity distributors and, lastly, the construction of a dedicated Heat Grid, often absent where NG pipelines are capillary. High temperature HPs such as double-stage and/or transcritical CO_2 are already available on the market. The first ones have lower COP while, the second ones need a high-temperature cold sink. In the end, Power-to-Heat as a storage option shows a higher conversion efficiency, e.g. direct electric heater or HP, but the issues move from losses of electricity storage to losses related to thermal storage. It implies a convenience if the heating demand is high but, contemporary, the severe weather conditions affect that efficiency. So, a Smart Heating concept should complement the above-mentioned Smart Electricity whereas separated from each other and both of them are to be regarded as essential for the implementation of sustainable energy systems [9]. Smart Heating involves two different Grids: the Gas Grid consisting of pipelines filled by fuels planned at national level and the Heat Grid made of pipelines filled by steam or water as thermal energy carrier built at local scale. This latter, known as District Heating, is an efficient technology to provide heat from industry waste or cogeneration plants in dense areas such urban context [10]. Feeding those new local infrastructures with Heat produced by synthetic fuels conversion is a first way to buffer RES intermittency and to merge electrical renewables with heating purposes. Moreover, synthetic fuels as final energy carriers and raw material could be integrated into existing Gas Grid without incurring excessive costs and technical constraints [11]. Power-to-Gas and Power-to-Liquid options play an important role alongside fossils, possibly in a complementary manner for Hybrid fuels such as Hydrogen enriched Natural Gas. Those technologies are essential to manage the energy transition being able to decarbonize the energy supply chain as fraction of Hybrid fuels [12], to allow higher share of RES as storage solution [13] and to be immediately used in existing energy systems [14] as well-proven fuels, even along with mechanical efficiency improvement, e.g. in CHP systems [15].

The authors investigated on storing renewable excess electricity by means of electrolysers to produce Hydrogen for contemporary heating and electricity purposes, allowing feasibility and competitiveness with established technologies in terms of primary energy consumption from large scale energy systems due to higher round trip efficiency. Waiting for cutting-edge control systems and ICT Smart Meters, Hydrogen is therefore meant as the physical link between Heat and Electricity in the transition towards Future Smart Energy Systems. Here, the authors analysed the potential energy benefits or drawbacks coming from the applications and deployment of hydrogen technologies for static power and heat production based on the state-of-the-art as well as on ones already available on the market to face the energy transition. Specifically, only well-proven technologies ready for accepting Hydrogen enrichment were considered.

2. Natural gas as the last fossil fuel

In the energy transition, the choice of the survivor source out of the fossil fuels is based on efficiency of its technology application and its availability for each Country. According to European Roadmaps and IEA analysis, Natural Gas should play an essential role in the energy transition towards National and Paneuropean low carbon systems. Natural Gas Combined Cycle is one of the most efficient technology solutions and it is the preferable one when a repowering strategy is planned. For instance, for Member States