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Modelling the integrated power and transport energy system: The role of power-to-gas and hydrogen in long-term scenarios for Italy

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A B S T R A C T

This work analyses future energy scenarios at country scale, focusing on the interaction between power and transport sectors, where Power-to-Gas is expected to play a key role. A multi-node model is developed to represent the integrated energy system, including additional electrical load from plug-in electric vehicles, energy storage, and hydrogen production from excess electricity for fuel cell vehicles. Electricity supply-demand balance is solved hourly, while liquid and gaseous fuels for mobility are accounted for cumulatively over the year. The Italian system is investigated, considering different evolution scenarios up to 2030 and 2050. The simulations yield a maximum 57% share of renewable sources in the electricity mix in 2050, while biomass could account for a further 5%. Results show that the use of Power-to-Gas increases the overall share of renewable sources across the sectors. High coverage of hydrogen mobility demand by clean production (about 81%) is achieved in presence of a large installation of renewables and a substantial introduction of fuel cell vehicles. However, greenhouse gas emissions reduction does not attain the ambitious long-term targets. In the best scenario, transport approaches the 60% cut, while power sector achieves only half of the desired 95% variation, thus calling for additional measures.

1. Introduction

In most countries, the energy system is undergoing profound modifications, mainly driven by the increasing concern about climate change. Besides the medium-term push on renewable energy sources (RES), greenhouse gas (GHG) emissions reduction, and energy efficiency measures with the 2020 and 2030 targets [1], the European Union (EU) is now committed to an 80% reduction of GHG emissions below 1990 level by 2050 [2]. This new objective is general, thus regarding all the sectors that involve consumption of energy in any form.

In recent years, a significant effort has been devoted to decarbonise power generation, with the installation of large capacity of RES-based power plants, especially wind and solar (from 80 GW in 2006 to 650 GW in 2016 cumulative installed capacity worldwide [3]). However, to meet the ambitious EU objectives, the transition must involve all the energy sectors. In particular, the second most relevant area in terms of carbon footprint is road transport, which accounted for about 27% of the final energy consumption [4] and 24% of GHG emissions [5] in Europe in 2015. Decarbonisation of transport requires a massive introduction of low- or zero-emission vehicles in replacement of conventional ones fed with fossil fuels, which are already encountering limitations in some countries (e.g., Norway and Netherlands). Plug-in electric vehicles[1] (PEVs) and hydrogen fuel cell electric vehicles[2] (FCEVs) both offer low or zero local pollution (NO_x, CO, particulate), but their impact on the overall system is different: PEVs increase the electrical load on the grid, hence requiring a further increase in low-CO_2 electricity generation, while FCEVs need clean hydrogen production pathways to be low-carbon solutions [6].

In this context, power generation and mobility are expected to interweave more and more, leading to a new structure of the

[1] The category 'Plug-in Electric Vehicles' (PEVs) includes both Battery Electric Vehicles entirely run on electricity (BEVs) and Plug-in Hybrid Electric Vehicles featuring a fossil fuel-fed ICE coupled with an externally rechargeable battery (PHEVs).

[2] The option of plug-in fuel cell electric vehicles, which would add the possibility of externally charge the on-board battery, has also been conceived, but it is not considered in this work.

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overall multi-energy system. Energy storage will be crucial to help the integration of clean sources and applications. While batteries may be installed to manage intermittent electricity generation on short time scales, the Power-to-Gas (P2G) technology is receiving attention as a valid long-term storage option [7]. It recovers excess electrical energy from non-programmable RES and feeds it to electrolysis devices that produce carbon-neutral hydrogen.

The topic of decarbonisation is broadly present in literature. Regarding the power sector evolution, studies have investigated the effects of high penetration of renewable sources in terms of backup generation [8], storage needs [9], and costs variation [10]. Space and time averaging of the energy profiles have been studied, comparing storage introduction to grid extension [11] or analysing various options for grid improvement [12]. Analyses on electrical energy storage technologies have evaluated various available power system applications [13]. Lately, P2G use and integration have gained attention, and some works have estimated the installation potential for excess electricity recovery in future high-RES electricity systems, e.g. in Italy [14] and Spain [15]. About the interconnection of networks, studies have looked at the interaction between power and natural gas grids, e.g. analysing the natural gas grid operation when highly dynamic consumption profiles occur due to intermittent power generation [16]. In terms of sectors coupling, analyses on electricity and heat have mainly investigated smaller geographical scale, like city [17] or district [18]. Attention to the transformation of the transport sector appears to be a more recent research effort, with a focus on the interaction of new mobility solutions with the power grid [19] and the effect on GHG emissions [20]. The importance of the integration of power and transport sectors is growing, in particular due to the rising amount of electric and fuel cell vehicles available on the market [21].

This work investigates the role of P2G in an integrated multi-energy system. Looking at future scenarios characterized by a large installed capacity of intermittent RES plants, a significant amount of excess energy is expected, which could be properly exploited by P2G systems for the production of hydrogen [22]. It is straightforward to look at hydrogen-based mobility as a suitable application for the generated clean fuel. A model is proposed to represent the power generation and the road transport sectors, and simulate their combined behaviour, with the aim of assessing the hydrogen potential and estimating its relevance in coping with the EU emission targets. The model is applied to Italy, which is a member state of the EU and therefore subject to the above-mentioned objectives. Two alternative evolutions of the power sector and two forecasts on vehicles distribution are considered, generating four different scenarios. Due to the punctual availability of data, the transport sector is limited to passenger cars and light-duty vehicles. However, the procedure is general and the analysis could be extended to the whole transport sector.

First, the features of the proposed model are detailed. Then, the simulation of future scenarios of the Italian system is presented: data and assumptions are outlined before discussing the results in terms of energy sources shares. A comparison between the analysed scenarios studies the possibility of achieving the GHG emissions targets set by the EU. Large quantities of installed RES are essential for a proper exploitation of storage, while a high share of innovative mobility solutions is required to obtain a positive impact on the system.

2. Methods

To assess the role of the Power-to-Gas technology in supporting the penetration of RES, a model has been developed that integrates the different sections of the energy system. Analysing the interactions over time of the energy flows, the aim is to evaluate the achievable shares of renewable energy sources exploited in each sector and the combined effects on the overall system. Future scenarios, characterized by different values of installed RES capacity and stock of vehicles, are the focus of this work. They are either based on forecasted evolution by diverse research studies or specifically built according to estimates of maximum technical potential (i.e. without considering economic and political limitations).

The representation of the system is based on a lumped nodal scheme, meaning that no detailed positioning of plants and loads is taken into account within each node (i.e. infinite capacity grid) and only inter-nodal exchanges are subject to constraints. For both power and mobility sectors, the considered nodes depend on the geographical scale, on a case-by-case basis, as well as on actual limitations of the infrastructure (e.g., single connection). For analyses at country scale, the nodes can correspond to electrical market areas, where they exist, or to regional grouping.

The logical structure of the analysis is schematised by Fig. 1, and it is discussed in the next sections together with the assumptions required by the model. The main parameters for the types of storage systems considered are summarised in Table 1. Minimum number of equivalent working cycles for batteries and minimum equivalent operating hours (EOH) for P2G are defined according to techno-economic viability, as further detailed in Section 3.

Table 1
List of parameters for the energy storage systems considered.

Parameter	Value
PHS roundtrip efficiency	72 %
BESS roundtrip efficiency	90 %
BESS lifetime	3000 cycles
BESS minimum equivalent working cycles	200 cycles/y
P2G efficiency	65 %
P2G minimum equivalent operating hours	1500 h/y

2.1. Power sector modelling

In this work, wind, solar, geothermal, and hydroelectric power plants are classified strictly as renewables (label ‘RES’), while biomass-based electricity generation is treated separately (label ‘bioenergy’) as it is programmable and not 100% carbon-neutral. Conventional generation includes fossil fuel-based power plants or import from adjacent countries (label ‘conventional’).

The model considers the requirement of constant balance between generation and load on the power grid at each time step (e.g., 1 h) over the considered time horizon (e.g., one year). The availability of excess electricity after RES generation is assessed and possibly exploited through large-scale storage systems: first, electric-to-electric solutions aimed at peak shaving and load shift

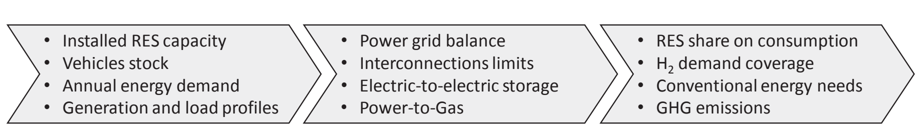

Fig. 1. Logical scheme of the developed method.