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Power-to-Gas integration in the Transition towards Future Urban Energy Systems

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ABSTRACT

Temperature levels play a key role in the thermal energy demand of urban contexts affecting their associated primary energy consumption and Renewable Energy Fraction. A Smart Heating strategy accounts for those supply features requiring new solutions to be effectively renewable and to solve the RES capacity firming. Power-to-Gas (P2G) is the way to decarbonize the energy supply chain as fraction of Hybrid fuels, combination of fossil ones and Renewable Hydrogen, as immediate responsive storage solution. While, Power-To-Heat is conceived as the strategy to modernize the high and medium temperature heating systems by electricity-driven machines to switch from Fuel-to-Heat to Electricity-to-Heat solutions. The authors investigated on different urban energy scenarios at RES share increase from 25% up to 50% in the energy mix to highlight strengths and weaknesses of the P2G applications. Primary Energy Consumption was chosen as the objective function. Three Reference Cities were chosen as reference scenarios. Moreover, the analytical models of P2G was designed and implemented in the reference energy system. The results of the twelve scenarios, four for each Reference City were evaluated in terms of amount of Renewable Heat delivered. Finally, the interaction between P2G and renewable heat production was evaluated.

The transition to Smart Heating

Sustainable energy supply is often synonymous of Renewable Energy Sources (RES). The increasing demand of RES integration in current and future energy systems entails technical, economic and social issues for handling the energy transition. Furthermore, the challenging targets of RES share set by COP meetings and Regional energy policies such as EU 2030 Roadmap [1] come from the translation of IPCC carbon emissions targets in related Primary Energy Savings (PES) [2]. Currently, the threshold value achievable without specific adjustments in the Electricity Grid, as it was conceived one hundred years ago, has been just reached in many Countries as the yearly average one. In details, the 25% RES is the breakdown value for total integration of RES in current energy

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Nomenclature

AHP Absorption Heat Pump
BER Berlin
CHP Combined Heat and Power
COA Coefficient Of Amplification
COP Coefficient Of Performance
DME Dimethyl Ether
EHP Electric Heat Pump
FC Fuel Cell
GEHP Gas Engine Heat Pump
GHG Greenhouse Gas
GUE Gas Utilization Efficiency
HP Heat Pump
HT High Temperature
HTs Heating Technologies
ICE Internal Combustion Engine
ICT Information and Communication Technology
KPH Copenhagen
LHV Low Heating Value
LT Low Temperature
LTHP Low Temperature Heat Pump
MC Molten Carbonate
MGT Micro Gas Turbine
MRC Micro Rankine Cycle
MT Medium Temperature
NG Natural Gas
P2G Power To Gas
P2H Power To Heat
PEC Primary Energy Consumption
PEM Proton Exchange Membrane
PES Primary Energy Saving
PTHR Power To Heat Ratio
PV/T Photovoltaic/Thermal
RES Renewable Energy Sources
RM Rome
SE Stirling Engine
SO Solid Oxide
SOFC Solid Oxide Fuel Cell
TSA Temperature Swing Adsorption

Abbreviations

COP_{GHP} GHP Coefficient Of Performance
COP_{HP} HP Coefficient Of Performance
$E_{D,el(HT)}$ Electrical Demand for High Temperature End-User
$E_{D,el(LT)}$ Electrical Demand for Low Temperature End-User
$E_{D,el(MT)}$ Electrical Demand for Medium Temperature End-User
$E_{D,H(HT)}$ Heating Demand for High Temperature End-User
$E_{D,H(LT)}$ Heating Demand for Low Temperature End-User
$E_{D,H(MT)}$ Heating Demand for Medium Temperature End-User
$E_{el,CHP}$ CHP electricity output
$E_{el,ELY}$ Electricity consumption of the electrolyser
$E_{el,exc(HT)}$ Electricity coming from CHP and RES over-productions
$E_{el,exc(MT)}$ Electricity coming from eventual MT machines electricity and RES over-productions
$E_{el,HP}$ HP electricity consumption
$E_{el,RES}$ Total renewable electricity
$E_{el,RES(HT)}$ Renewable electricity for High Temperature End-User
$E_{el,RES(LT)}$ Renewable electricity for Low Temperature End-User
$E_{el,RES(MT)}$ Renewable electricity for Medium Temperature End-User
$E_{fuel,AGHP}$ AGHP fuel consumption
$E_{fuel,Boiler}$ Boiler fuel consumption
$E_{fuel,CHP}$ CHP fuel consumption
$E_{fuel,Cond.Boiler}$ Condensing Boiler fuel consumption
$E_{fuel,sys}$ Total primary energy consumption
$E_{fuel,sys(HT)}$ Primary energy consumption of High Temperature End-User
$E_{fuel,sys(LT)}$ Primary energy consumption of Low Temperature End-User
$E_{fuel,sys(MT)}$ Primary energy consumption of Medium Temperature End-User
$E_{fuel,sys(TOT)}$ Total fuel consumption
$E_{Grid(HT)}$ Electricity supplied by Power Grid for HT End-User
$E_{Grid(LT)}$ Electricity supplied by Power Grid for LT End-User
$E_{Grid(MT)}$ Electricity supplied by Power Grid for MT End-User
$E_{H,AGHP}$ AGHP thermal output
$E_{H,Boiler}$ Boiler thermal output
$E_{H,CHP}$ CHP thermal output
$E_{H,Cond.Boiler}$ Condensing Boiler thermal output
$E_{H,HP}$ HP thermal output
E_{H2} Energy content of produced Hydrogen
E_{REX} Renewable Electricity excess
ES_{H2} Fraction of Hydrogen energy on the fuel energy content
$E_{wasted,CHP}$ Energy wasted by the CHP
f_{CB} Fraction of MT heating supplied by Condensing Boiler
f_{RES} Renewable fraction of electricity
F_{RES} Renewable Energy Fraction
$PTHR_{CHP}$ CHP Power To Heat Ratio
R_{res} Percentage of Renewable Electricity Excess

Greek symbol

ε_{BOIL} Heat exchanger effectiveness for boiler
ε_{CHP} Heat exchanger effectiveness for CHP
$\eta_{el,CHP}$ CHP electrical efficiency
$\eta_{el,Grid}$ Power Grid efficiency
η_{ELY} Electrolyser efficiency
η_{h} Condensing Boiler thermal efficiency
$\eta_{hr,CHP}$ CHP heat recovery efficiency
$\eta_{I\ Law}$ First Law efficiency

systems without large-scale storage facilities to solve the renewable capacity firming [3]. Of course, during the day the fluctuating renewable production excedes the aforementioned value up to 50%, twice of the tolerated value. A recent research compared the different storage technologies calling for strong integration across traditionally separate energy sectors in order to identify the cheapest solution. For instance, its authors argued that electricity storage is the most mentioned solution even if, in certain conditions, it is approximately 100 times more expensive than thermal storage and even more expensive than storage for gases and liquids [4].

Among those other options, Power-to-Heat (P2H) solution by means of Heat Pumps can be considered promising [5]. Indeed, since it is the most efficient heating technology owing to its Coefficient of Performance (COP), it has to be carefully introduced in existing energy systems owing to it works at low input-output temperature (e.g. hot water at 55 °C). When its use would replace conventional systems several adjustments are required: firstly, the new low temperature supply needs larger size of the end-users terminals, secondly, it entails a further electrical load to the local electricity distributors and, last but not least, starting from supplying building complexes it could be effective if a new dedicated Heat Grid is built [6]. In Countries where the heating systems depend on fossil fuels, the fuel supply infrastructures are often capillary widespread and the heat production is close to its consumption. Yet, this is also a barrier for harvesting waste heat since large heat producer such as power plant are equipped with fuel supply to be fed rather than pipelines to supply this produced heat. If a Power-to-Heat strategy would be effective, it must meet the required temperature level required by the end-user side. To do so, Medium and High temperature HPs are already available but, their performance is lower or much lower than the aforementioned Low Temperature one (LTHP) and their associated cold heat sink must be at higher temperature than external air, often considered as the free source for LTHPs. Beside the Power-to-Heat, another option, different from the Power-to-Power (P2P) solutions such as battery, is the Power-to-Gas (P2G) [7]. This latter was already discussed to integrate high RES share involving the future transport sector composed by Natural Gas (NG), methanol (DME) and Electric Vehicles (EV) fleet stating that for the large-scale integration of fluctuating renewable electricity sources, system balancing and flexibility can be reached by means of P2G [8]. The suitability of the Gas derived from renewable electricity excess for the energy systems was analysed accounting for the features of the established Gas Grid. The foreseeable way is to integrate into existing Gas Grid the Renewable energy carrier without incurring excessive costs and technical constraints [9]. Then, Hydrogen is identified as the Gas to be produced by means of electrolysers fed by intermittent renewables when they overcome the 25% RES share threshold. The choice is made since it plays an important role alongside fossils, possibly in a complementary manner for Hybrid fuels such as Hydrogen enriched Natural Gas. Handling the energy transition corresponds to being able to decarbonize the energy supply chain as fraction of Hybrid fuels [10], to mitigate the shock for the Grid derived from high peaks of RES share fluctuations as immediate responsive storage solution [11]. Furthermore, it is equivalent to have a fuel which can be immediately used in existing energy systems [12] as well-proven fuels, even along with mechanical efficiency improvement, e.g. in Combined Heat and Power (CHP) systems [13].

The authors investigated on storing renewable excess electricity by means of P2G technologies focusing on meeting the heating demand and its different temperature levels. Rather than adopting forthcoming technological solutions [14], cutting-edge control systems and ICT Smart Meters, the Power-to-X technology is, therefore, meant as the link between Heat and Electricity in the transition towards Future Urban Smart Energy Systems. Here, the authors analysed the potential energy benefits or drawbacks coming from the applications and deployment of different heating systems and hybrid-fuel based technologies for static power and heat production based on the state-of-the-art as well as on those ones already proven and available on the market for the P2G scenario. Specifically, only well-proven technologies ready for accepting Hydrogen enrichment were considered. Then, P2G application was analysed to evaluate its potential achievable benefits. Therefore, a preliminary analysis on yearly base was carried out by building an aggregated energy system model with a normalized energy demand and the heating one equal to 100 dimensionless units will be analysed for each supply temperature level with Renewable Hydrogen and with Renewable electricity-driven Heat by measuring the effects of those implementations.

Scope of the article

The study focuses on Power-To-Gas application in energy transition scenarios towards Future Smart Urban Energy Systems. Assessing the contribution of feasible P2G integration by means of well-proven technologies is the first step to promote the merging between electricity and heating sectors and to establish other viable renewable supply alternatives on the market for moving to synergies among all the energy sectors. A key point is considering the different temperature levels of current heating systems which require specific thermal machines to guarantee to meet the thermal energy demand in quantity and quality. Then, the application of P2G technology was considered. The research questions this study answered are:

1. What Heating Technology could be involved in energy efficiency improvement but considering the different temperature levels of energy needs?
2. What kind of contribution, in terms of Primary Energy Saving and RES excess mitigation, could be provided by the implementation of P2G with those Heating Technologies when the share of RES fluctuates from 25% to 30%, 40% and 50% in the energy mix?

While several studies focused on enhancing the efficiency of electricity systems by means of P2G such as the second reserve for high intermittent renewables [15] or by means of seasonal storage and alternative carriers [16], the authors investigated on how P2G can make more renewable the heating supply, by means of environmentally-friendly

Hydrogen-based fuels. Basically, in this paper the outcomes of this study could be integrated in more effective energy distribution infrastructures to accomplish international energy-related CO_2 reduction targets.

To do so, an overview of Heating Technologies is provided in Section Heating technologies at high, medium and low temperature and in Section Methodology an energy system model was built by the authors. Then, all of the Equations to implement the HTs within the model are presented in Section Analytical models for heating technologies implementation in energy scenarios. Finally, in Section Results and discussion the results of HTs implementation and the scenarios with changes in RES share are discussed.

Heating technologies at High, Medium and Low Temperature

Renewable capacity firming could not be solved by the simple coupling of Heat Pumps and electrolysers. For this reason, technological solutions for heating purposes should be considered along their overall efficiency to each achievable maximum supply temperature. Specifically, High Temperature is considered at about 85 °C, such as for conventional boilers; Medium Temperature is related to around 65 °C such as for Gas Engine Heat Pump or Domestic Hot Water production; and, finally, Low Temperature belongs to about 45 °C such as for electric Heat Pumps.

In this way, the quality of heat is balanced by the quality of the demand for an effective match and a lower PEC. To perform the simulation of different energy scenarios, the most common Heating technologies are considered. In detail, an overview of those already available on the market and forthcoming ones for electricity-based heating production is presented below.

CHP technologies overview

Nowadays, one of the most common options for supplying efficiently the energy to end-users consists of installing combined heat and power (CHP) generators which convert fossil and bio fuels into both electricity and heat. For this reason, European Union by Directive 2004/8/EC [17] promoted officially the CHPs wide diffusion over the Members States in order to develop the so-called distributed generation. Due to the achievable significant primary energy saving, which entails higher GHG (greenhouse gas) emissions reduction [18–20], this technical solution has been well proven in the past especially in large industrial applications, where a great amount of thermal and electrical energy supply is required at lower prices. Furthermore, thanks to the recent technology advances in materials and electronic control systems, CHP plants became attractive also for managing heating and cooling in large and small civil applications such as district heating and building air conditioning. Indeed, by the use of an absorption and adsorption chillers or desiccant dehumidifiers [21,22] as heat recovery devices it is possible to extend the CHPs operating hours and to generate efficiently cool water or cool air for several purposes [23,24]. Up to date, several conversion technologies are already accessible in commercial and pre-commercial versions. Here, the Fuel Cell-based CHP system fuelled with hydrogen represents a promising solution due to its high electrical efficiency ranging in 15%–60% [25], excellent partial load performance, modular applicability along with vibe and noise-free operation. Thus, the FCs can be fuelled directly or indirectly with hydrogen, and they are categorized by the electrolyte type in PEM (proton exchange membrane), MC (molten carbonate) and SO (solid oxide). Yet, the hydrogen is considered as an energy carrier and for this reason it has to be produced. That implies to build a dedicated hydrogen distribution infrastructure when the centralized production model is adopted. Currently, the well-known CHP technologies consist of MGT (Micro Gas Turbine), MRC (Micro Rankine Cycle), SE (Stirling Engine), ICE (Internal Combustion Engine) and FC (Fuel Cells) [17]. All of these technologies are not directly comparable each other on the basis of conversion efficiency values due to their different minimum sizes, fuels typology and temperature level of hot water production. For those reasons, the choice of the most suitable technology is strongly dependent on the energy system operating temperature as well as the demand curves profile for both heating and power. It is important to point out that a wide number of CHP manufactures for large scale plants can be found all over the world. Those machines are typically able to provide hot water characterized by a maximum supply temperature ranging between 70 °C–120 °C, or to generate on-site superheated water steam in several manufacturing processes. On the contrary, only a few models and companies are available on the market for low temperature applications [13], i.e. for water supply equal to 40 °C–55 °C, and an added condensing heat exchanger is often required for that purpose. Additionally, those engines are categorized as micro CHP systems due to their small rated electrical power output, which is usually lower than 20 kWel. As a consequence, they represent a viable option for decreasing the primary energy consumption of the most common energy systems such as multi-family houses, sport centres or indoor swimming pools and small-medium enterprises as well. In the end, it is noteworthy to mention the SOFCs (solid oxide fuel cell) as the most promising CHP configurations. The growing interest on their development is due to the fact that they are characterized by high energy efficiency, fuel flexibility, modularity and the absence of corrosive liquids [28]. Thus, those devices have a typical operating temperature ranging in 450 °C–800 °C depending on their electrical size and constructive solution, favouring their use as a CHP to meet both high and low temperature thermal needs. Notwithstanding, the main drawbacks consist of a low reliability and duration when they are daily switched on and off owing to thermal fatigue onset which significantly reduces the solid electrolyte lifespan. A remarkable advantage of SOFCs is that H2 is not the only fuel option. At high operating temperature, other fossil sources, such as carbon and hydrocarbons, can be activated and then used for feeding [29]. To do so, hydrocarbons are often reformed to hydrogen rich gas externally or internally in the SOFCs by means of a fuel processor. In that case the SOFCs can be considered a variant of NG-based CHP plants. As regards the CHP energy balance modelling, it can be calculated by the following fundamental equations:

$$\eta_{el,CHP} = \frac{E_{el,CHP}}{E_{fuel,CHP}} \tag{1}$$

where $E_{el,CHP}$ is the electricity output and $E_{fuel,CHP}$ is the energy consumption from fuel. Similarly, the heat recovery efficiency $\eta_{hr,CHP}$ is defined as:

$$\eta_{hr,CHP} = \frac{E_{H,CHP}}{E_{fuel,CHP}} \quad (2)$$

where the $E_{H,CHP}$ is the thermal energy output. Moreover, another parameter to characterize completely the CHP is the Power-To-Heat Ratio $PTHR_{CHP}$ as reported in Equation (3).

$$PTHR_{CHP} = \frac{E_{el,CHP}}{E_{H,CHP}} \quad (3)$$

While, the energy wasted by the CHP is described below.

$$E_{wasted,CHP} = \left[1 - \left(\eta_{el,CHP} + \eta_{hr,CHP}\right)\right] E_{fuel,CHP} \quad (4)$$

GHP technologies overview

The most common HPs devices are generally based on vapour-compression cycle or chemical compression by means of absorption or adsorption cycles. Thus, HPs can be divided into several categories according to their driving energy sources, such as electric driven HPs (EHPs), chemical HPs, ground source HP, geothermal energy HP, solar assisted HPs and/or hybrid power systems etc. [26–29] and gas engine driven HPs (GEHPs). Usually, fuel is converted to electrical energy by large power plants connected to the national grid, and their waste heat is discharged to the environment. The transmitted electrical energy feeds the EHPs and it is converted again into mechanical energy by compressor electrical motor. As a consequence, the primary energy is converted twice within the overall process and heat losses are high. The growing interest in GEHP was due to the possibility to enhance the energy efficiency in heating processes once fuel conversion has been located closer to where heat is required [30]. A GEHP layout generally consists of a vapour compression HP with an open compressor, driven by a NG internal combustion engine (ICE). Even though the conversion efficiency of an ICE is limited to modest values (e.g. 30%–45% at rated power output and depending on engines size), the waste heat of fuel combustion can be recovered up to 80% approximately [31]. The heat recovery architecture is quite similar to the CHP one. Specifically, it is usually done by means of a liquid to gas heat exchanger so as to subtract thermal energy from high temperature exhaust gas and by utilizing the waste heat released by the engine cylinders jacket [31–33]. In Fig. 1, the common layout for a reversible GEHP and pathways of working fluids flows were shown.

Basically, from the energy point of view the GEHPs are equivalent to a cascade system composed of a CHP and EHP, where engine mechanical output can be partially converted either in electricity for hybrid devices [35] or to drive directly the HP compressor. Having said, the GEHPs are able to provide hot water up to 60 °C - 65 °C with a typical COP (alternatively GUE and COA acronyms can be found in literature) equal to 1.2–1.9 depending on their constructive concept and the outdoor environmental temperature changes as well [36,37]. Finally, it is important to point out that NG engine-driven systems show less efficiency degradation with increased hot

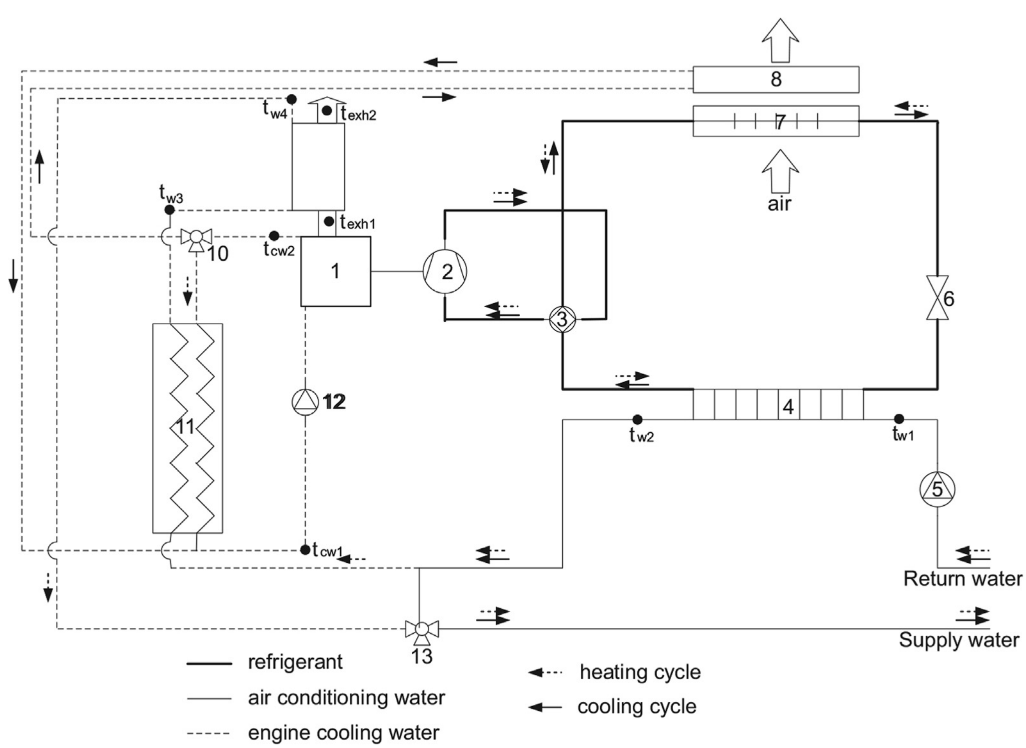

Fig. 1 – Schematic diagram of GEHP drawn by Zhang et al. [33,34]: (1) natural gas engine, (2) open compressor, (3) four-way valve, (4) plate-heat exchanger, (5) supply water pump, (6) expansion valve, (7) finned-tube heat exchanger, (8) heat radiator, (9) gas-to-water heat exchanger, (10) three-way valve, (11) water-to-water heat exchanger, (12) cooling water pump, (13) three way valve.

water temperature than electrically driven systems [38] favoring their application within medium temperature end-users. Among thermally driven devices the absorption heat pumps (AHP) are the most popular. Those machines are able to shrink energy costs at high temperature lifts, but are less favorable than mechanically driven ones, owing to their lower COP. Referring to the common layout as reported in Fig. 2, absorption HP does not require a mechanical compressor and consequently the electricity.

Instead, high quality heat is needed at the liquid absorber regenerator in order to drive the refrigerants desorption process. The vapour is then condensed out in the condensing heat exchanger to get the desired temperature of end-user working fluid. After the condensation process the liquid pressure is reduced, allowing heat to be transferred from a low temperature source. Finally, the refrigerant is absorbed within the absorbent material by means of an exothermic chemical reaction releasing heat at temperatures close to the process one for cycle closing. It has been shown in literature [40–42] that absorption heat pumps are a suitable option in several industrial processes providing the hot water temperature in the range 55 °C–60 °C and typical COP equal to 1.2–1.6 depending on the working pairs (i.e. refrigerants/absorbers) [39]. Differently, in the case of adsorption cycles the refrigerant is adsorbed in the pores of a solid sorbent such as zeolite, silica gel, activated carbon, expanded graphite, activated carbon fibres, vermiculite, metallic foams, and their operating principle is thermodynamically similar to the absorption ones. Since the working pairs consist of a vapour and solid sorbent material, this latter cannot easily be moved from one vessel to the other like for liquid ones. As a consequence, adsorption cycle becomes a discontinuously working process and the two phases can occur successively in the same vessel. Notwithstanding, to ensure a reasonably continuous useful heating or cooling effect, two different reactors are usually required and they have to operate in counter-phase. Fig. 3 shows a typical constructive solution of an adsorption heat pump. It is noteworthy that during the phases changing, a short period without cold/heat production followed by a peak in the heat/cold generation occurs. Hence, the cycling time becomes a more crucial control parameter compared to the pump rate in those machines.

Currently, several concepts and architecture were developed by manufacturers related to adsorbent heat recovery, heat exchanger, and vessels when shifting the phase, so as to reduce the efficiency decrease owing to the lack of a liquid solution heat exchanger. For this purpose, some marketed version opted for using only one reactor operating alternatively in adsorption and desorption mode offsetting the interruption of thermal power supply by an oversized NG burner integration [44–46]. According to that technical solution, Fig. 4 depicts the working principle of a heat pump prosed by Vaillant [47]. In detail, that hybrid appliance has two different exchanger modules, incorporating two heat exchangers. The top one operates either as a desorber or an adsorber, while the lower heat exchanger works respectively as a condenser or evaporator. Thus, the working pairs consist of water as refrigerant and zeolite in the form of loose pellets between the fins of a finned-tube adsorber heat exchanger. One of the most interesting features of this product is the use of solar collectors or PV/T as an ambient heat source. Finally,

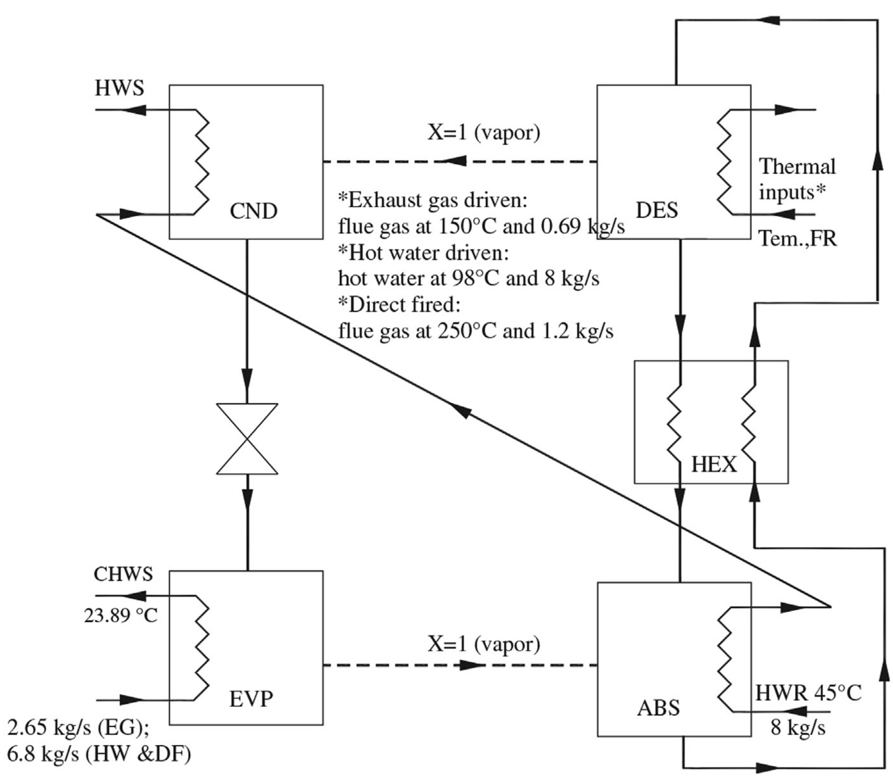

Fig. 2 – Absorption heat pumps components layout. Source: [39].

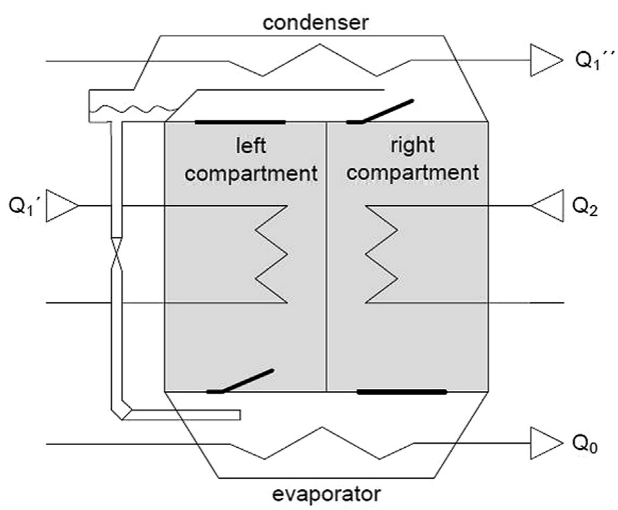

Fig. 3 – Adsorption heat pump basic layout. Source [43].

the Vaillant GHP is able to provide hot water up to 75 °C with a COP ranging in 1.2–1.35.

Having said, it is possible to state that all of the GHP technologies show better environmental and energy performance than any gas boilers and for those reasons they represent the next generation gas boiler version.

Integration of Power to Gas option in complex energy systems for heating purposes

It is well known how wind and solar energy play an important role to get better energy and environmental performance at national, regional and local scale, according to the Renewable Energy Roadmap 21 promoted by the European Commission. Notwithstanding, the increasing RES share in national electricity supply mix implies the adoption of several storage technologies in order to mitigate the mismatch between electricity demand and production curves. Among those ones, the Power to Gas solution might contribute positively to tackling both grid safety and balancing issues [48], especially for long-term energy storage systems [49,50]. To do so, the P2G process is able to merge the power grid to the NG one by converting the electricity excess into a compatible gas flowing through existing NG facilities, via a two-step process: hydrogen production hailing from water electrolysis and hydrogen conversion, by means of catalytic reactions with the external CO and CO_2 sources, deriving from carbon capture infrastructures nearby or onsite. It is noteworthy that, if the electricity excess is completely renewable, the hydrogen carbon footprint can be considered basically equal to zero and the fluctuating capacity of renewable power plants can be levelled [51]. Several P2G concepts and layouts such as hybridization with air separation plants, biogas plants, biomass gasification, sewage plants, fossil power plants or industrial processes (e.g. oil refinery) [52] have been recently considered to obtain the source of carbon dioxide. Moreover, in order to effectively recover and use the vented-out oxygen from electrolysers, a P2G subsystem can be integrated in an oxy-fuel combustion system as reported in literature [53,54]. Even though the main output of Sabatier reaction is synthetic methane, the waste heat due to the exothermic energy associated to that chemical reaction, can be considered a secondary useful product. Indeed, the most common operating temperature and pressure of catalytic reactors are equal to 300 °C and 8–30 bar, respectively. Under those thermodynamic conditions, the heat recovery for cooling down the synthetic methane stream line flowing through the Sabatier reactor, is suitable and for instance, it can be discharged into either a district heating network or other industrial processes requiring high temperature thermal energy. In addition, the carbon dioxide capture and

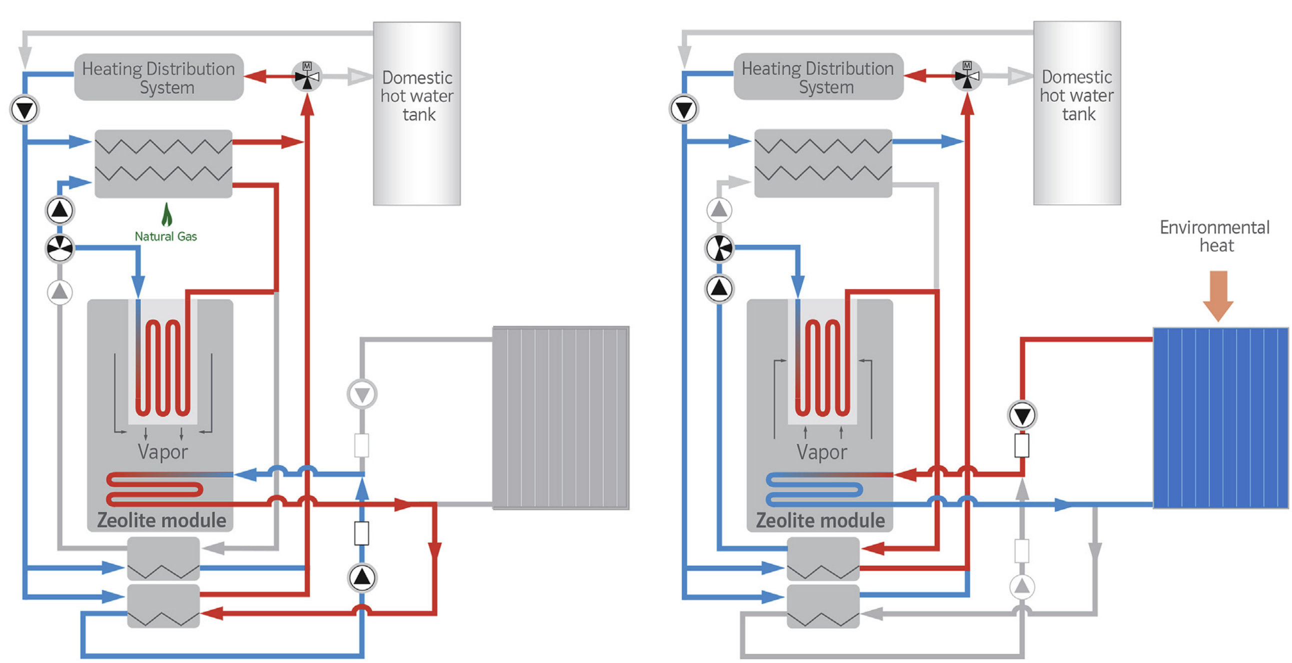

Fig. 4 – Vaillant gas-driven heat pump during desorption phase (left) and the adsorption phase (right). Source [47].

purification plants offer the possibility to recover more heat depending on the capture technology in a wide temperature range, i.e. 40°-150 °C. Indeed, CO_2 compression-trains with storage systems and CO_2 entrapment by zeolite-based reactors for applying the TSA (Temperature Swing Adsorption) method allow to recover heat from compressors intercooler, residual water remover, superheated steam produced by CHPs, and from the energy carrier sub-cooling required by the TSA. Having said, an alternative use of the so called renewable hydrogen would be direct injection of H_2 into the NG grid, as widely discussed in Ref. [55]. Anyway, it is important to point out that the amount of H_2 in the gas grid is limited by country specific standards and regulations so as to assure the correct operating conditions of the most common end-user devices. The main drawbacks of Power-to-Gas are a relatively low efficiency and high costs [56,57], which can be mainly attributed to the hydrogen generation plants along with the carbon capture and purification ones. Indeed, referring to the current hydrogen market maturity, P2G projects are viable and cost effective only if very large electrolysers are installed so as to use the beneficial effects deriving from the scale economy. Finally, in Countries where NG Grid is not widespread also infrastructures for methanol option can be taken into account based on recent energy storage assessment [58].

Methodology

The aim of this study is to create alternatives in terms of technology scenarios for supplying heating at different temperature levels and electricity with Renewable Hydrogen and with Renewable electricity-driven Heat by measuring its contribution in primary energy supply, system efficiency, Renewable fraction of the total energy supply and, specifically, the amount of delivered Renewable Heat. For this purpose, a preliminary analysis on yearly base has been carried out by building an aggregated energy system model with a normalized energy demand and the heating one equal to 100 dimensionless units will be analysed for each supply temperature level, as reported in Fig. 5.

Specifically, the link between Renewable Energy Sources and Heating supply is the field of the study.

Reference model

By a further zoom in of the previous layout, Fig. 6 depicts the most used Heating technologies for each considered temperature level. At High and Medium Temperature the technology could be defined Fuel to Heat with the only exception of the CHP which Fuel to Heat and Electricity. While, the Low Temperature is the only proven Electricity to Heat.

The Equations to build the energy system model are outlined below. Referring to the High Temperature (HT) End-User, its Electricity Demand $E_{D,el(HT)}$ appears in:

$$E_{D,el(HT)} + E_{el,exc(HT)} = E_{Grid(HT)} + E_{el,RES(HT)} + E_{el,\ CHP} \tag{5}$$

where the electricity is supplied by the National Grid, the RES production and the CHP output. $E_{el,exc(HT)}$ represents the electricity coming from CHP and RES over-productions when they occur. While, the Heat Demand at high temperature is met by CHP thermal output and the Boiler one.

$$E_{D,H(HT)} = E_{H,CHP} + E_{H,Boiler} \tag{6}$$

The HT primary energy consumption $E_{fuel,sys(HT)}$ is reported in Equation (7):

$$E_{fuel,sys(HT)} = \frac{E_{Grid}(HT)}{\eta_{el,Grid}} + E_{fuel,CHP} + E_{fuel,Boiler} \tag{7}$$

As regards, the Medium Temperature End-User, the Electricity Demand $E_{D,el(MT)}$ is:

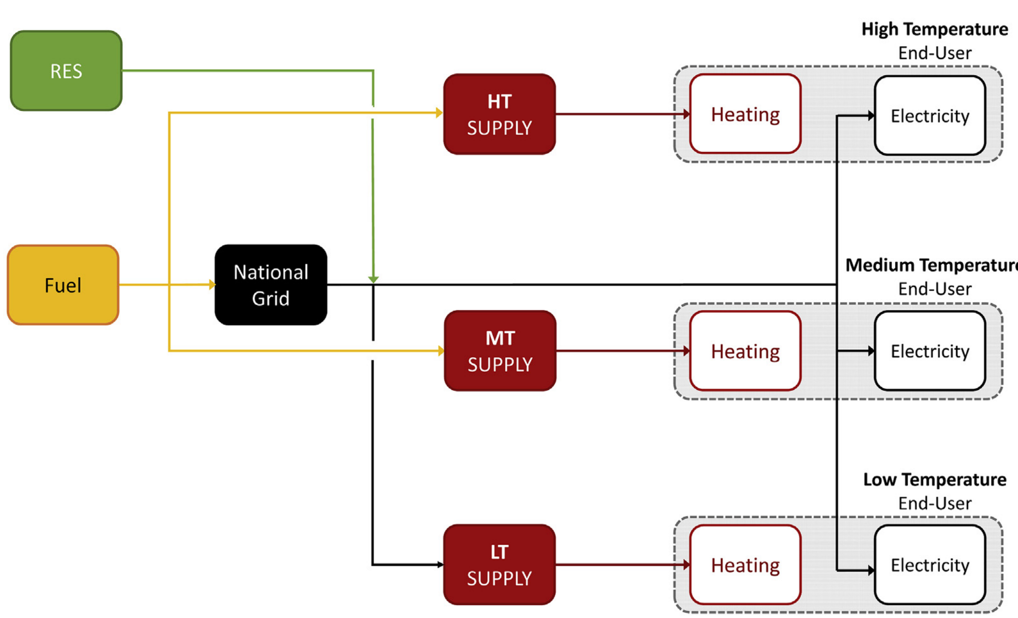

Fig. 5 – Energy system model to meet electricity and heating demand at different temperature levels by National Grid and Distributed Generation.

$$E_{D,el(MT)} + E_{el,exc(MT)} = E_{Grid(MT)} + E_{el,exc(HT)} + E_{el,RES(MT)} \tag{8}$$

where the electricity is supplied by the National Grid and the RES production. Similarly, $E_{el,exc(MT)}$ represents the electricity coming from eventual MT machines electricity and RES over-productions when they occur. While, the Heat Demand at medium temperature is met by AGHP thermal output and the Condensing Boiler one.

$$E_{D,H(MT)} = E_{H,AGHP} + E_{H,Cond,Boiler} \tag{9}$$

The heating produced by the Condensing Boiler could be fixed as a fraction of $E_{D,H(MT)}$.

$$E_{H,Cond.\ Boiler} = f_{CB} \cdot E_{D,H(MT)} \tag{10}$$

The MT primary energy consumption $E_{fuel,sys(MT)}$ is shown below.

$$E_{fuel,sys(MT)} = \frac{E_{Grid(MT)}}{\eta_{el,Grid}} + E_{fuel,AGHP} + E_{fuel,Cond,Boiler} \tag{11}$$

The Electricity Demand of the Low Temperature End-User is reported in Equation (12):

$$E_{D,el(LT)} + E_{el,HP} = E_{Grid(LT)} + E_{el,exc(MT)} + E_{el,RES(LT)} \tag{12}$$

where the electricity is produced by the National Grid and the RES production. While, the Heat Demand at low temperature is met only by HP thermal output.

$$E_{D,H(LT)} = E_{H,HP} \tag{13}$$

As a consequence, the LT primary energy consumption $E_{fuel,sys(LT)}$ reads as:

$$E_{fuel,sys(LT)} = \frac{E_{Grid(LT)}}{\eta_{el,Grid}} \tag{14}$$

Finally, the PEC of the entire energy systems can be obtained by adding all the temperature levels PECs, as shown in Equation (15):

$$E_{fuel,sys(TOT)} = \sum_{j=1}^{N} E_{fuel,sys(j)} \tag{15}$$

$$E_{REX} = R_{res} \cdot \sum_{j=1}^{N} E_{el,RES(j)} \tag{16}$$

where E_{REX} is the electricity excess when the 25% of RES share is overcome.

Then, f_{RES} is the renewable fraction of electricity, i.e. the ratio between the total $E_{el,RES}$ and all electrical consumers. In the base case, they consist of the HP and the Electricity Demand.

$$f_{RES} = \frac{\sum_{j=1}^{N} E_{el,RES(j)}}{\sum_{j=1}^{N} E_{D,el(j)} + E_{el,HP}} \tag{17}$$

While, the overall Renewable Energy fraction F_{RES} is defined as:

$$F_{RES} = \frac{\sum_{j=1}^{N} E_{el,RES(j)} + E_{h,RES(j)}}{\sum_{j=1}^{N} E_{D,el(j)} + E_{D,h(j)}} \tag{18}$$

An analytical constraint is expressed in Equation (19), representing the fixed fuel consumption of the CHP as independent of its electrical efficiency.

$$\frac{d(E_{fuel,sys(TOT)})}{d(E_{el,\ CHP})} = 0 \tag{19}$$

Finally, the Power To Heat Ratio for Demand side PTHR was defined below.

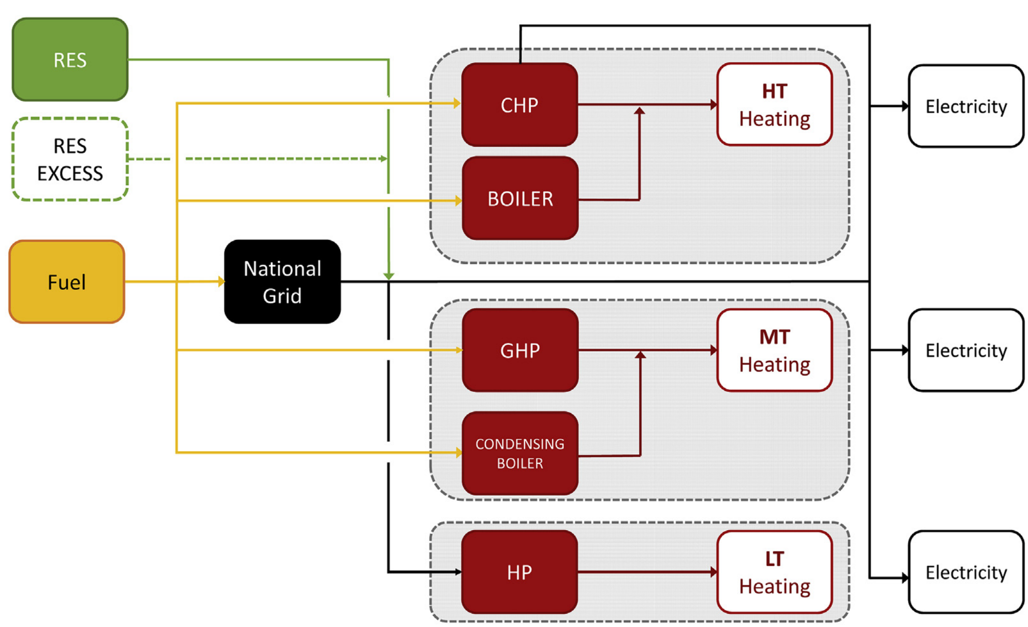

Fig. 6 – Energy system model with detailed thermal energy production by well-proven technologies to meet heating demand at different temperature levels.

$$PTHR = \frac{E_{el,D}}{E_{h,D}} \tag{20}$$

To focus on Heating sector analysis, the Heating demand was normalized as 100 dimensionless units as shown in Equation (21):

$$E_{D,H(HT)} + E_{D,H(MT)} + E_{D,H(LT)} = 100 \tag{21}$$

Therefore, for each temperature level the associated Electricity demand was calculated as proportion of the PTHR of the considered Urban Model. The National Grid efficiency η_{Grid} was assumed equal to a competitive value of 0.42, as forecasted for the transition scenarios in 2030 by Ref. [59]. It is noteworthy that long term scenarios could be further improved if P2G is implemented at National scale by prioritizing policy actions [60] and/or even if applied at sector level such as heavy industry in manufacturing-based economies [61].

Reference end-user: PTHR and urban energy systems

Identifying the PTHR of the end-user provides information about the quality of the energy demand. Based on TABULA database [62], a link was found between building construction date, climatic conditions and their thermal performance as well as the most common installed heating technologies. From data analysis, it emerges that the older the building the higher the share of heating on the total energy consumption and, consequently, the lower the PTHR. Modelling the PTHR of urban building stock could provide the base for handling the transition from high temperature fossil fuel-based thermal energy production to low temperature renewable-based one, i.e. the road towards Smart Heating. Having said, within Cities different building stock are present and spatially distributed. For instance, high PTHR values could be associated to new buildings since their high insulation to reduce the heat losses is coupled to medium or low temperature heating systems or even electricity-based such as HP. Therefore, their location is far from the historic urban centre. This latter, on the contrary, has low PTHR values since first installed heating systems were high temperature based and the existing Gas Grid was dedicated to them. So, temperature levels are directly connected to the technology: where historically high energy demand was to meet, HT systems were installed while, when low temperature could be provided since high efficiency of the building envelope is present, electricity-based heating solutions were preferred. Indeed, Electricity Grid was the first way to connect modern urban tissue as network of consumers. Making more efficient building stock is often challenging for extremely diverse reasons. Two cases could be considered emblematic: on one hand, historic or even listed buildings show many constraints in changing the heating systems due to the lack of space, the architectural values to preserve which are obstacle for energy retrofitting interventions and the need to redesign the heating terminals, not replaceable, for substituting the temperature supply towards a lower one. On the other hand, in public housing built after the Second World War, required energy efficiency measures are so huge to make the investment ineffective due to the nature of ownership as well as the contrast between big centralized heating systems and poor quality building envelope. Taking into account the proportion of historic, modern and contemporary building stocks as well as their temperature level of heating supply, it was possible to design ten urban end-user mixes, as reported in Fig. 7. They are characterized by a PTHR varying from 0.13 to 0.283, which corresponds to heating temperature distribution of 70%–20% - 10% and 20%–40% - 40% for high, medium and low temperature, respectively. The extreme scenarios and a middle one were selected and associated to the most similar real cities to make clearer to the reader the link between building age, location and heating demand quality. Specifically, the PTHR

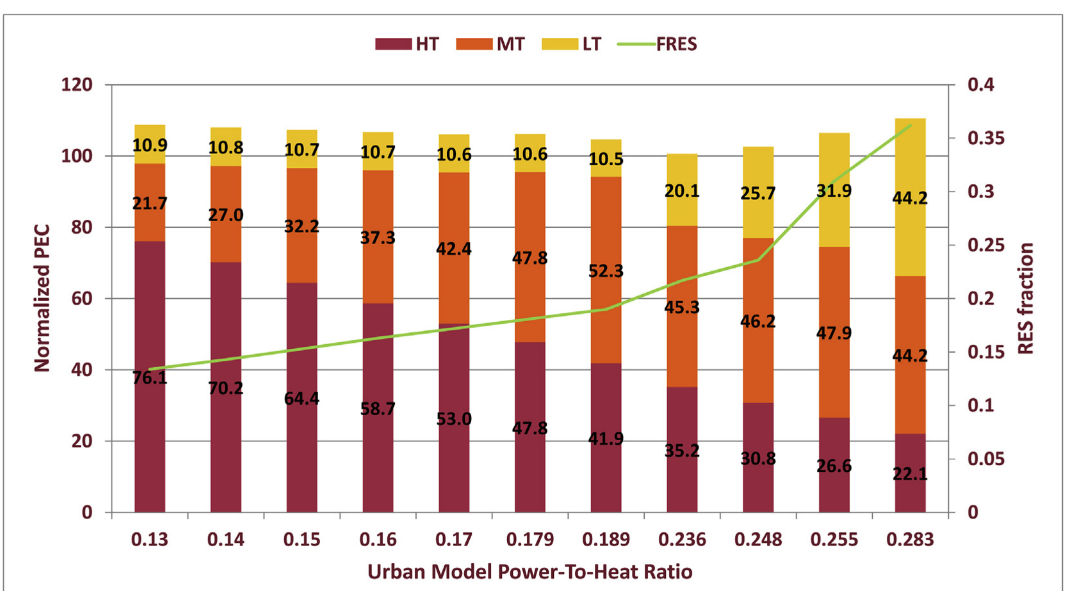

Fig. 7 – Normalized Primary Energy Consumption vs. Urban Model Power-To-Heat Ratio along with its Renewable Energy Sources fraction.

0.13 is representative of Rome, PTHR 0.189 of Berlin and PTHR 0.283 of Copenhagen.

Climatic conditions affect level of insulation and, consequently, opportunity to provide lower temperature heat. From a thermal energy perspective, the proportion between HT and MT demand does not affect so much the Normalized Primary Energy, as shown in Fig. 7. This is the case of all PTHR values range from 0.13 to 0.189. When the LT quote rises, the Normalized PEC and total RES fraction increase as well. Indeed, the Urban models PTHR ranging from 0.236 to 0.283 show the high slope of RES fraction line since, for a comprehensive calculation, the aerothermic sources of the HPs were included. So, the RES fraction accounts for the RES share and the free cold heat sink of the HPs. Therefore, the larger HP supply to meet LT demand, the higher the amount of Renewable energy, which is actually integrated in the system. It is noteworthy that for PTHR values between 0.248 and 0.283, the substitution of HT heating systems with LT ones entails an increase of PEC as well as a reduction of System efficiency, as depicted in Fig. 7. This is due to LT heating systems are fed by electricity and the Grid supply along with its efficiency affects the calculation. Coherently, the amount of Renewable energy rises considerably. Nevertheless, Fig. 8 shows a PEC trend almost stable for PTHR ranging from 0.13 to 0.189, the partial substitution of HT with MT heating solutions implies an improvement of System efficiency owing to the choice for more efficient fuel to heat conversion systems. Furthermore, the mentioned improvement is independent of the Grid efficiency since the electricity-driven LT technologies share in all the Heating demand remains constant at 10%. For the purpose of this study, three Urban Model PTHR were chosen along with the identification of real Cities they can represent. In detail, Rome, Berlin and Copenhagen were associated to the PTHR values equal to 0.13, 0.189, 0.283, respectively. This choice is based on the survey of the building stock which composes those urban environment and, subsequently, the typology of heating demand as well as the required temperature level of supply currently installed.

For instance, Rome heating systems are based on distributed boilers from Natural Gas and Diesel based centralized ones supplying heat to condominium to small ones, mainly feeded by Natural Gas, for meeting the heating demand of each flat. Great part of them provides HT heat. A small percentage of building was refurbished alog with the re-sizing of new heating terminals due to the installation of MT heating systems such as Condensing Boilers. Moreover, only new buildings are equipped with LT solutions such as air-to-air electric HPs. In Fig. 9 the energy-flow-diagrams of the three Reference cities meeting 100 dimensionless thermal energy units with a RES share of 25% are depicted. It is remarkable that the merging between heat and electricity production is already feasible for the Copenaghen case in the HT end-user. Indeed, at this temperature level, the CHP is the only working machine which provides all the heating and electricity demand along with a surplus of this latter. Running the CHP as an efficient heat generator allow to get HT heat and to use electricity to reduce Grid supply, as a first attempt to promote distributed generation. The importance of this statement is highlighted by the fact that the CHP production is quite similar in all the scenarios even if the HT quote is diverse. In that sense, the key role for HT heating supply is played by the Boiler. In the Rome and Berlin optimized energy scenarios, the Grid could be switched off allowing to produce electricity locally by CHP and RES. In Copenaghen case, the Grid is needed primarly to meet the electricity demand of the HP, linking the LT heating production to the National Grid efficiency as well as in terms of Primary Energy Consumption. At MT heating supply, the Gas-engine Heat Pump is the main provider of absolute amount of heat in all the scenarios assisted by the Condensing Boiler. The Copenhagen scenario shows a high electrification of the total energy demand even if the electricity required by the LT systems is not considered. As aforementioned, the PTHR identify the ratio between electricity and heating demand to characterize the end-user and it varies from 13 electricity units per 100 heat units for Rome, 18.9 electricity units per 100 heat units for Berlin and 28.3

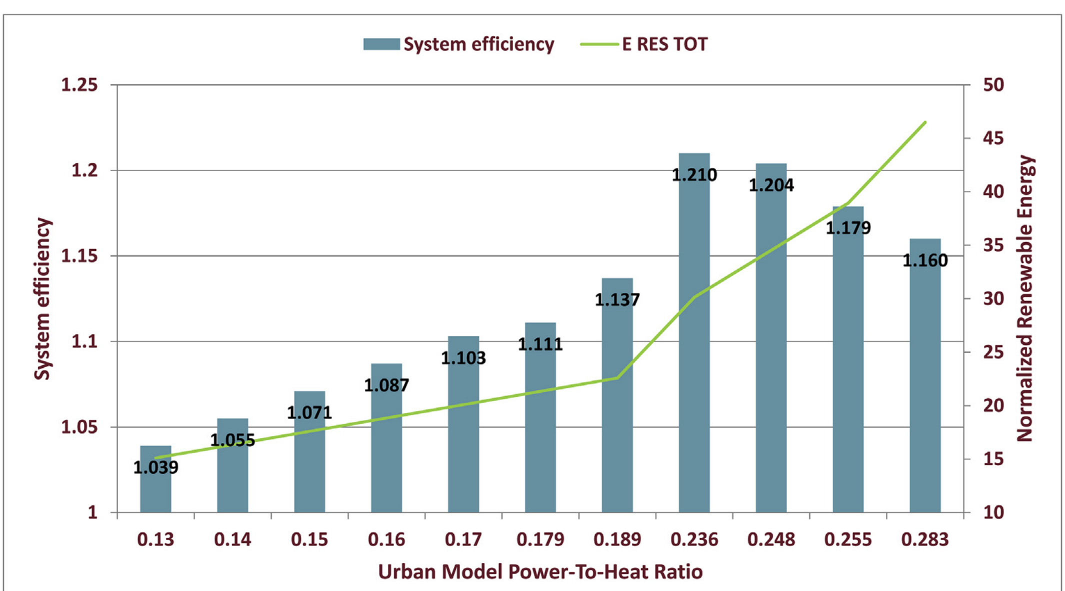

Fig. 8 – System efficiency vs. Urban Model Power-To-Heat Ratio along with its Normalized Renewable Energy.

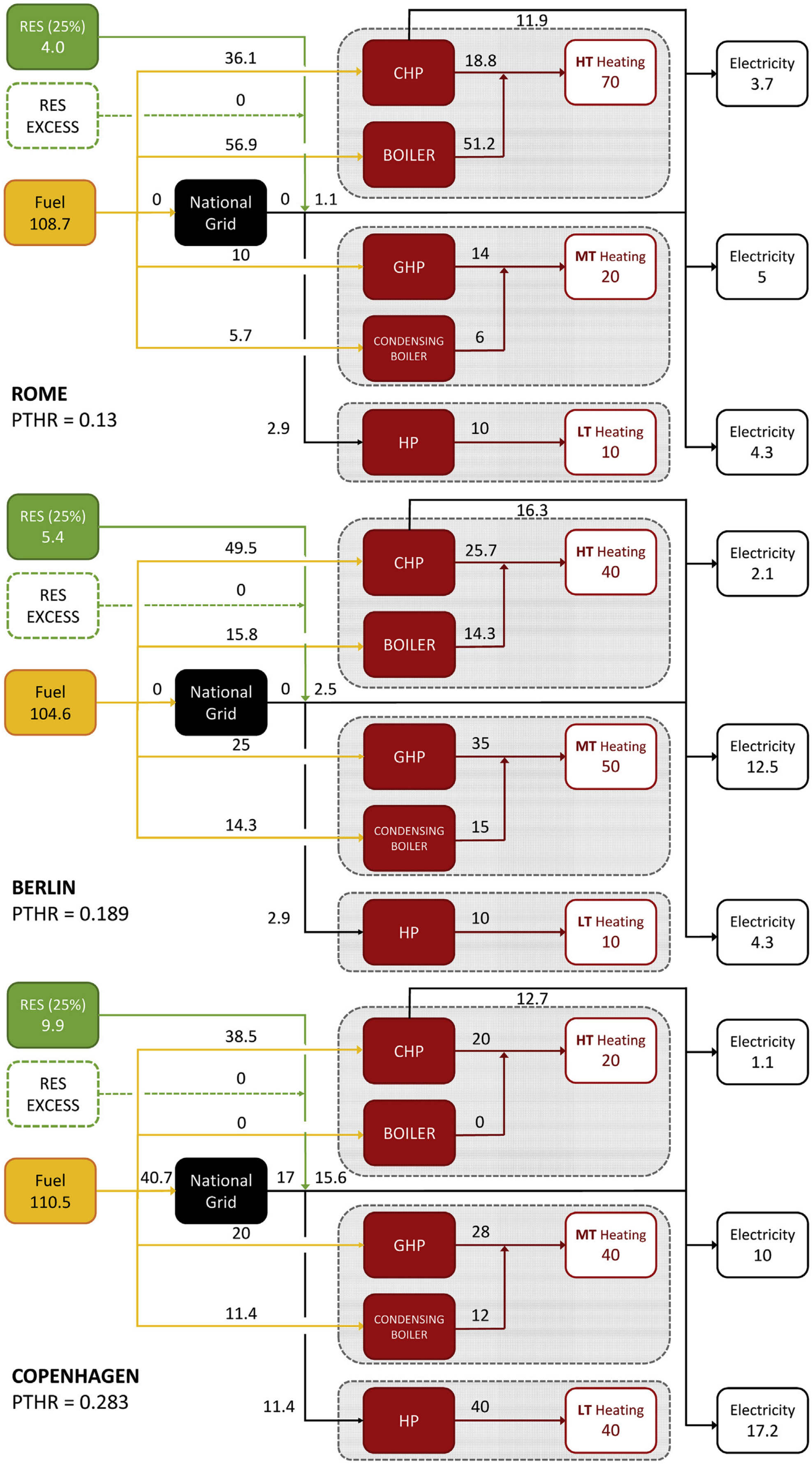

Fig. 9 – Energy-flow-diagrams of the three Reference cities meeting 100 dimensionless thermal energy units.

electricity units per 100 heat units for Copenhagen. If also the power to feed the HP is counted, the electricity units per 100 heat ones become 15.9, 21.8 and 39.7 in Rome, Berlin and Copenhagen cases, respectively.

Renewable energy penetration in the systems at different temperature levels is analysed with changes in the RES share in electricity. As abovementioned, the threshold 25% is widely considered as the limit value of integration without requiring storage facilities. Yet, daily fluctuation of intermittent renewable production provides to the system situations where this instantaneous value is up to 50%. Those cases were analysed as shown in Fig. 10 in order to evaluate how much RES could be effectively integrated in current energy systems architecture and what effect it has on the PEC.

At 25% of RES share, all the Reference Cities show the highest PEC value. Doubling the RES share entails the largest Primary Energy Saving in Copenhagen scenario owing to all the LT electricity-driven heating systems are fuelled with RES. Consequently, their high COP provides a leverage effect on reducing the PEC. While, in RM and BER cases, even though the same temperature level electricity supply is covered by RES, its low share, i.e. 10%, implies greening the electricity demand of the end-users as well partially substituting the Grid supply. Then, as depicted in Fig. 11, the System efficiency rises at RES share increasing in all the scenarios. The largest change is related to the KPH scenarios since its η_{sys} rises from 116% to 148%. The same trend is observed for the Normalized Renewable Energy. As regards this latter variable, again KPH has the best performance overcoming the 50% of the total energy demand. It is noteworthy that the aerothermic source of the LT HPs was considered as part of the renewable supply for a complete assessment of the energy flows. Referring to the RM and BER scenarios, when twice the reference RES share is integrated the system efficiency slightly increases of 5 and 7% points, respectively. From Fig. 11, it emerges that when the RES share goes up to 50% in RM case, its η_{sys} is still not competitive with the same value for KPH case at 25% of RES share. Whereas the maximum renewable integration of BER case has the same performance of KPH one at 30%.

It is remarkable that, since the share of the HT, MT and LT heating demand determines the associated PEC, improving the demand side appear as the key strategy. That means approaching the road towards low energy buildings equipped with LT heating. In other words, the first step towards the Smart Heating concept. On the other hand, even if KPH scenario has the highest LT heating demand, it needs a RES share of 40% to be competitive with RM at 50% in terms of PEC. Therefore, at low RES share, the Grid contribution to meet the electricity demand from the electric-driven heating systems calls for accounting the National energy mix as most important factor.

Finally, having showed the beneficial role played by increasing RES share on the PEC and system efficiency, independently of the temperature levels distribution, the authors investigated on possible benefits coming from P2G application to integrate more effectively up to 50% of RES share. As aforementioned, until the threshold value equal to 25% those options could be avoided as well other storage solutions. Hence, they were identified as the technological drivers for Future Smart Urban Energy Systems. At the same time, once the RES share scenario is fixed, real time data and proven operational database could make further accurated the thermal management strategies for urban environments such as district heating networks [63] or conventional high efficiency solutions [64].

Analytical models for heating technologies implementation in energy scenarios

Given that high PTHR entails high RES penetration, the authors investigated on the potential convenience of systemic

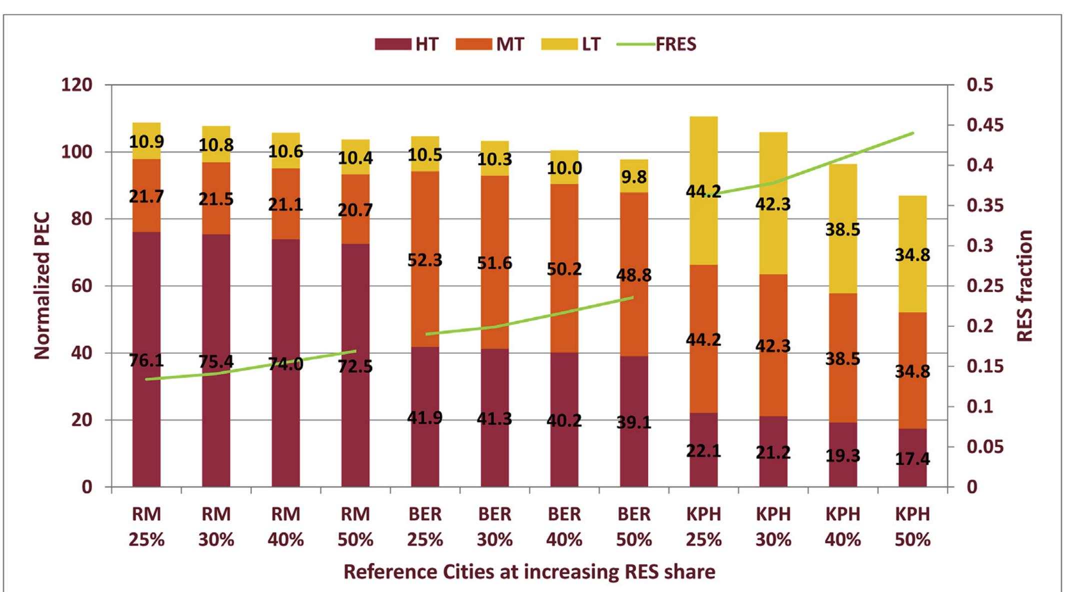

Fig. 10 – Normalized Primary Energy Consumption vs. Reference Cities scenarios at increasing RES share of electricity demand along with its Renewable Energy Sources fraction.

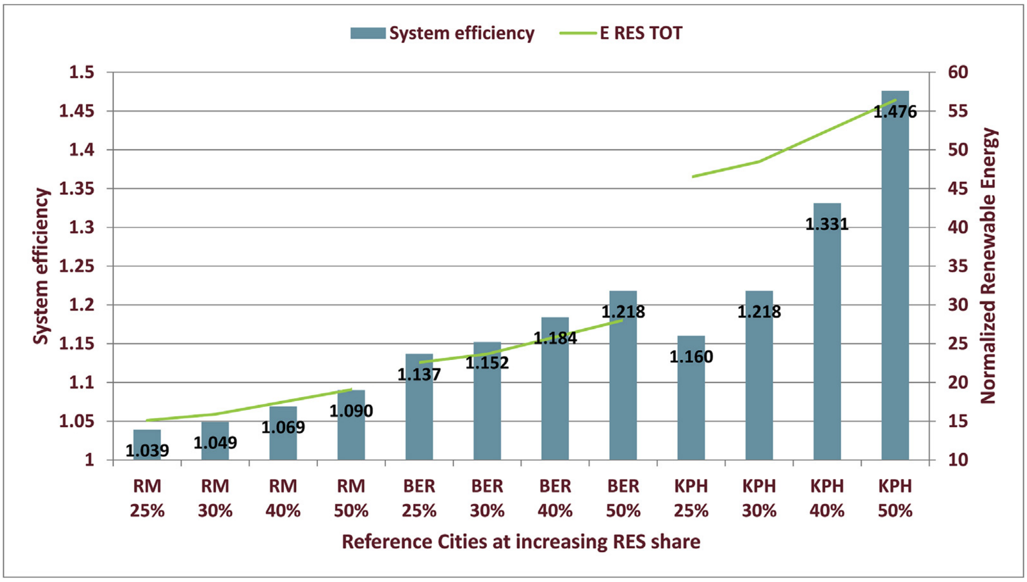

Fig. 11 – System efficiency vs. Reference Cities scenarios at increasing RES share of electricity demand along with its Normalized Renewable Energy.

Heating Technologies in the reference urban energy scenarios. This study focuses on primary energy savings thanks to the implementation of the following option considered in these simulations:

- Power To Gas by means of Renewable Hydrogen from electricity excess – P2G;

Finally, the new analytical terms related to Heating Technologies in the energy system balance Equations are highlighted in bold.

P2G Power to Gas integration

Once the Hydrogen has been produced by an electrolytic process and used to enrich the Natural Gas as a fraction of energy.

$$E_{H2} = E_{el,ELY} \cdot \eta_{ELY} = E_{REX} \cdot \eta_{ELY} \tag{22}$$

E_{H2} is the energy content of produced Hydrogen referred to its LHV and $E_{el,ELY}$ is the electricity consumption of the electrolyser. $E_{el,ELY}$ is superimposed equal to all the electricity excess, to link the P2G directly to the RES capacity firming. The

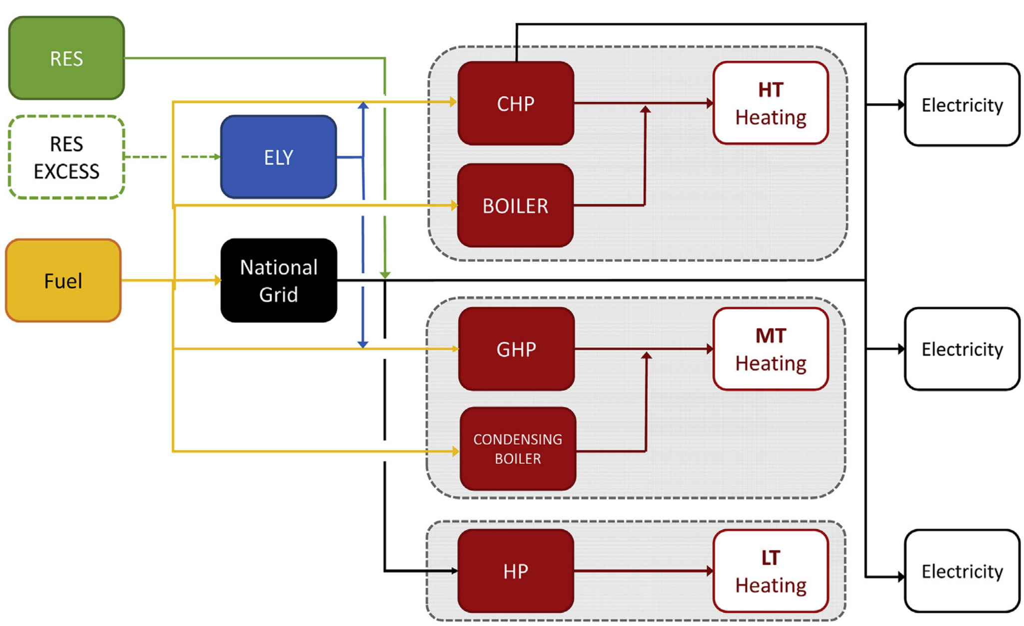

Fig. 12 – Energy system model with well-proven technologies to meet heating demand at different temperature levels and Power-To-Gas integration.

Table 1 – Calculation parameters for the HT, MT and LT heating technology scenarios.

Temperature level	Heating technology	Parameter	Value
HT	CHP	η_{el}	0.33
		η_{hr}	0.52
		$\eta_{I\ Law}$	0.85
		$PTHR_{CHP}$	0.635
		ε_{CHP}	0.6
	BOILER	η_h	0.9
		ε_{BOIL}	0.6
MT	COND. BOILER	η_h	1.05
	GHP	COP_{GHP}	1.4
LT	HP	COP_{HP}	3.5

electrolyser efficiency η_{ELY} is equal to 0.65 Hydrogen LHV based.

$$ES_{H2} = \frac{E_{H2}}{E_{fuel,CHP} + E_{fuel,Boiler} + E_{fuel,AGHP} + E_{fuel,Cond.Boiler}} \quad (23)$$

where ES_{H2} is the fraction of Hydrogen energy on the fuel energy content for partly substituting fossil fuel supply.

$$E_{fuel,sys(TOT)} = \sum_{j=1}^{N} E_{fuel,sys(j)} - E_{H2} \quad (24)$$

So, the total fuel consumption is reduced by E_{H2} as in Equation (24). The energy system layout with P2G integration is shown in Fig. 12.

Results and discussion

In this section, the outcomes of performed simulations have been discussed. Those simulations are related to the model built by the authors to answer the two research questions, mentioned in Section Scope of the article. All of results were determined by an optimization process by minimizing the objective function, i.e. the primary energy consumption. In detail, the technological options, i.e. P2G, and four RES shares in the electricity demand were combined to design twelve energy scenarios, four for each urban model. Additionally, the amount of actual Renewable Heat delivered by the energy systems was computed over all the simulated scenarios. In Table 1, all of parameters used for performing scenarios simulation are outlined.

The P2G along with its further technical assumptions were presented in Section Results and discussion. Furthermore, the RES share was assumed step by step equal to 25%, 30%, 40% and 50%. It is important to point out that:

- the 25% RES share is representative of the current average energy context for Countries which adopted the Kyoto Protocol and the break-down value for total integration of renewables without the installation of large-scale storage facilities;
- the 50% RES share is considered the target of Energy transition policies in the next 20 years and the upper limit of feasible renewables integration in the well-established energy system paradigm, i.e. conventional market and present infrastructures layouts [1].

Heating technologies energy scenarios with 30% - 40% - 50% of RES share with P2G

The first technological solution to be integrated in the energy scenarios is the Power-To-Gas. As discussed in Section P2G power to gas integration, the HT and MT heating systems were fuelled by hydrogen enriched fuel so as to partly greening the fuel supply by Renewable Hydrogen produced by means of electrolysers fed by RES electricity excess. It is possible to state tha the system layout technology switches from Fuel-to-Heat to Low carbon Fuel-to-Heat solution.

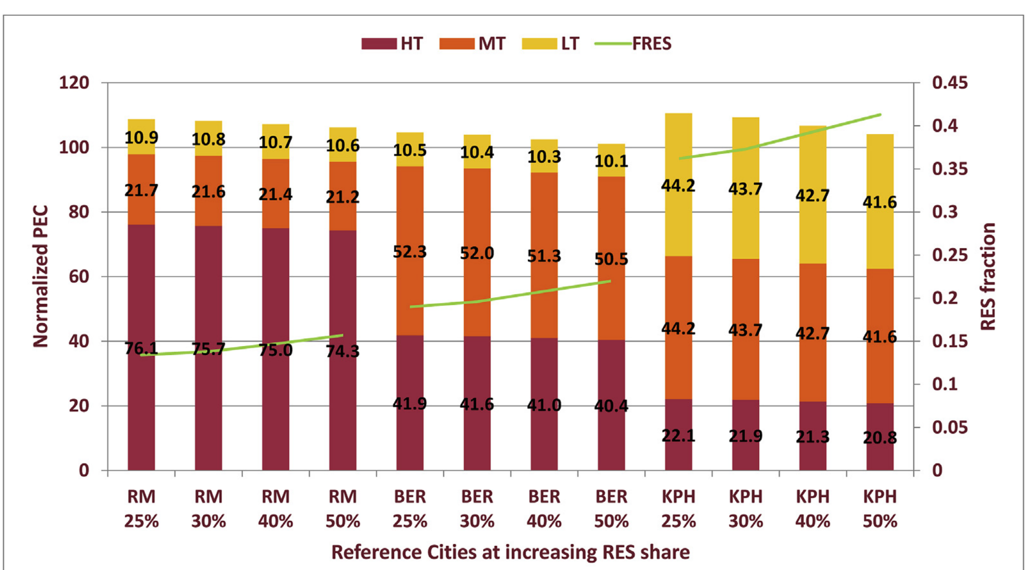

Fig. 13 – Normalized Primary Energy Consumption vs. Power-To-Gas integrated Reference Cities scenarios at increasing RES share of electricity demand along with its RES fraction.

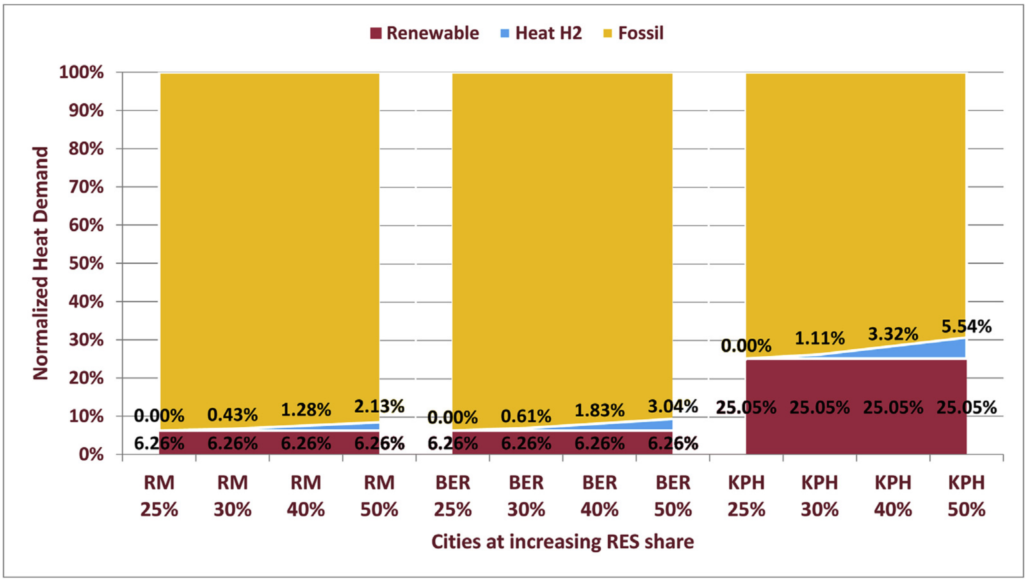

Fig. 14 – Renewable, Hydrogen-based and Fossil Normalized Heat Demand vs. Power-To-Gas integrated Reference Cities scenarios at increasing RES share of electricity demand.

Fig. 13 depicts similar Normalized PEC trend in all the energy scenarios at increasing RES share after P2G application.

This is due to the fact the H_2 derived from electricity excess conversion affects HT and MT fossil based systems. At 25% the P2G do not give a contribute since it works only thanks to the electricity excess from this value. A further 25% RES share converted in Hydrogen determines absolute PEC reduction equal to 2.58, 3.54 and 6.45 for RM, BER and KPH case, respectively.

Even though Hydrogen is conceived to be co-fired with methane to partially decarbonize combustion systems at HT and MT, as previously studied in [65,66], the results of the simulations shown in Fig. 14 seem to be controversial since after P2G application, the best performance belongs to KPH case. Here, the LT heating systems play a key role and they are electricity-driven. Actually, the fuel partial substitution affects all the supply temperature levels directly for HT and MT and indirectly through the contribution to the electricity produced by the National Grid. In the RM and BER scenarios, the Renewable Heat coming from H2, produced by RES excess from 25%, contribution is lower than the one provided by the LT fuelled with 25% of RES. Indeed, the electricity conversion to H_2 entails a further inefficiency in the system. While, in the case of KPH, the sum of H_2– related Heat and the renewable coming from LT HP fed by 25% RES share is high. The absolute amount of H_2-related heat is higher than the other two reference cities scenarios because, here, P2G allows to make more renewable the fossil fuel supply for HT and MT. Contemporary, indeed, the RES share has completely covered the LT HP electricity demand. The highest H_2-related heat is 5.54% for KPH case at 50% of RES share where, 25% is dedicated to that purpose and the other 25% to the mentioned HP electricity demand.

Synthetic fuels play a crucial role since HT demand associated to some uses such as healthcare facilities, industrial sites or, to remain within building sector, listed and historic buildings. By those fuels, it is possible to decarbonize the Fuel-to-Heat systems which in the current energy transition represents large part of the demand. Building sector heating supply could be downgrade to low temperature but it is not the only heating end-users when scaling-up is done from urban to regional or even National Energy Systems. Furthermore, for specific use Fuel-to-Heat remains the most efficient and reliable source for HT supply.

To conclude, further link is foreseeable with transport sector where fuel produced by carbon recycling and renewable capacity firming will allow to merge all the three energy consumer sectors: electricity, heating and transport. To do so, a forthcoming opportunity is done by studying the RES penetration up to 100% at least of the electric renewables to observe what temperature level distribution performs better and how its connection to the third sector could be effectively made.

From the outcomes of this study, the P2G plays the role of unlocking further beneficial effects coming from renewable energy integration as well as handling its excess.

Concluding remarks

The authors wanted to explore a road that would be investigated from further researchers by presenting their findings and showing the potential of their first outcomes. In order to perform simulations of twelve energy scenarios with changes in RES share and fuel-driven heating solutions at different temperature levels, a steady-state aggregated energy system model was built. By this model a parametric analysis of different Energy Demand composition associated to Reference Urban Models was carried out to evaluate the benefits in terms of PEC, System efficiency, Renewable Energy fraction and, above all, Renewable Heat. The results can be summarized as follows:

- Different temperature levels play a key role in characterize the energy demand of each Urban context affecting their energy demand, associated fuel demand and Renewable Energy Fraction.
- Power-to-Gas is the way to decarbonize the energy supply chain as fraction of Hybrid fuels, combination of fossil ones and Renewable Hydrogen, to mitigate the shock for the Grid derived from high peaks of RES share fluctuations as immediate responsive storage solution.
- An optimization process based on minimizing PEC as the objective function was performed. Three Urban Models were chosen as reference scenarios and their PEC were determined at 25%, 30%, 40% and 50% RES share, respectively.
- The analytical model of P2G was designed and implemented in the reference energy system. It entails the addition of electrolysers devices to convert electricity excess to Hydrogen and the installation of fuel-based heating suppliers accounting for HT, MT and LT levels.
- The System efficiency rises at RES share increasing in all the scenarios. The largest change is related to the KPH scenarios since its η_{sys} rises from 116% to 148%.
- In the P2G scenario, the best performance belongs to KPH Urban Model even if it has the highest LT share on heating demand. It seems to be controversial but, actually, the fuel partial substitution affects all the supply temperature levels directly for HT and MT and indirectly through the contribution to the electricity avoiding the one produced by the National Grid.
- At 50% of RES share, a Renewable excess of 25% is converted in Hydrogen determining an absolute PEC reduction equal to 2.58, 3.54 and 6.45 for RM, BER and KPH case, respectively.
- The highest H2-related heat is 5.54% for KPH case at 50% of RES share where, 25% is dedicated to that purpose and the other 25% to the mentioned HP electricity demand.
- It is possible to state that foreseeable policy targets of RES share equal for all the Countries along with their National Energy Systems, provoke so diverse fraction of renewability of the system in the energy mix of their Grid and, subsequently, on the entire electricity + heating systems.

To account for actual quantitative impact of high renewable share on the energy consumption and interaction with other Power-To-X technologies, a dynamic study is required. This latter will be the object of a second work of the same authors.

Finally, it is important to affirm that:

The Power-To-Gas option by Renewable Hydrogen production enables more effectively the transition towards Renewable Heating by providing its partial decarbonizing effect on the fuel supply at HT and MT levels. So, it promotes the NG greening, the merging heat with electricity sectors and it provides a real opportunity to link RES share higher than 50% to even the transport sector.

Acknowledgements

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