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Power-to-gas leverage effect on power-to-heat application for urban renewable thermal energy systems

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ABSTRACT

High Renewable Energy Sources (RES) share in energy systems entails environmental advantages in its use but drawbacks in its distribution, management and effectiveness. The interconnection between electricity, heat and transport sector seems to be a comprehensive answer. Its actual link is on-going and, currently, involves electricity and heat. Indeed, Power to Heat (P2H) is the strategy of meeting the heating demand by supplying electricity to feed Heat Pump (HP). Their higher efficiency compared to fossil fuel boilers requires a further check in the quality of the heating demand to meet, i.e. the temperature levels. Great part of current building stock calls for High Temperature (HT) Heat which is not affordable by HP maintaining their Coefficient of Performance. To face this issue, RES can be used to produce synthetic fuels for feeding existing energy systems, the so-called Power-to-Gas option. In this way, greening the fuel supply can be seen as the best option for meeting HT heating demand while, Medium and Low Temperature are met by HP. Therefore, two technological scenarios, P2H and its combination with P2G, are presented and assessed in three reference Urban Energy Systems. The authors investigated on the impact of RES share increase from 25% up to 50% in the electricity mix with the objective function of Primary Energy Consumption (PEC). The outcomes of twenty-four energy scenarios, eight for each Reference City were assessed also through the value of delivered Renewable Heat. Finally, the leverage effect of P2G on the system is evaluated in terms of renewable heat contribution.

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Nomenclature

2s-HP Two-stage Heat Pump
AGHP Absorption Gas Heat Pump
BAU Business As Usual
BER Berlin
CHP Combined Heat and Power
CO_2 Carbon Dioxide
COP Coefficient Of Performance
EHP Electric Heat Pump
EHTs Electric Heating Technologies
HEX Heat Exchanger
HP Heat Pump
HT High Temperature
HVAC Heating Ventilation Air Conditioning
KPH Copenhagen
LHV Low Heating Value
LT Low Temperature
LTHP Low Temperature Heat Pump
MT Medium Temperature
NG Natural Gas
P2G Power to Gas
P2H Power to Heat
PEC Primary Energy Consumption
PEF Primary Energy Fraction
PTHR Power To Heat Ratio
RES Renewable Energy Sources
RM Rome
UK United Kingdom

Abbreviations

COP_{GHP} GHP Coefficient Of Performance
COP_{HP} HP Coefficient Of Performance
COP_{HP2s} Two-stage HP Coefficient Of Performance
COP_{HPCO2} CO2 Trans-critical 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
$E_{el,HP(2s)}$ Two-stage HP electricity consumption
$E_{el,HP(CO2)}$ CO2 Trans-critical 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
$E_{H,HP(2s)}$ Two-stage HP thermal output
$E_{H,HP(CO2)}$ CO2 Trans-critical HP thermal output
E_{H2} Energy content of produced Hydrogen
$E_{in,HP(CO2)}$ Two-stage Heat Pump cold heat sink
E_{REX} Renewable electricity excess
ES_{H2} Fraction of Hydrogen energy on the fuel energy content
$E_{waste,Boiler}$ Energy wasted by the Boiler
$E_{waste,CHP}$ Energy wasted by the CHP
f_{RES} Renewable fraction of electricity
F_{RES} Renewable Energy Fraction
$PTHR_{CHP}$ CHP Power To Heat Ratio

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
$\eta_{h,Boiler}$ Condensing Boiler thermal efficiency
$\eta_{h,CondBoiler}$ Condensing Boiler thermal efficiency
$\eta_{hr,CHP}$ CHP heat recovery efficiency
$\eta_{I\ Law}$ First Law efficiency

Electrification and synthetic fuel production

Intermittency and unexpected increasing trends in harvesting Renewable Energy Sources, mainly electrical ones, entail changes in distribution, networks, markets up to affect the user behaviour [1]. High share of RES in electricity systems seems to open the road towards electrification of all energy-related sectors both with a centralized and a distributed energy system layouts [2], providing the opportunity to decarbonize local electricity systems and Grid supply lowering its primary energy factor [3].

When electrification is meant for heating, the so-called Power-to-Heat solution (P2H), many issues rise. First of all, electric heater, the simplest electric-driven heating production, has a low round-trip efficiency when compared to fossil-fuel boilers [4] and it is viable only where the price of electricity is low such as in Countries with large hydropower, i.e. Canada or Norway. This issue can be overcome with the installation of Heat Pump that performs better than fossil fuel-based solutions up to −10 C of outdoor temperature [5]. Yet, initial investment cost of substitution and of upgrade required to the electricity meter are immediate barriers to deal with [6]. Third, even if they are faced by dedicated incentive schemes and distribution adjustments [7], the main question is related to the new offered temperature level of the HP-produced heat and the temperature for what heating distribution and emission systems as well as the building were designed and built [8]. As matter of fact, several studies identified P2H as an interesting demand side management strategy [9] tested for wind and solar integration [10]. Beneficial results come from its application to Urban Energy Systems providing flexibility for large renewable energy penetration [11]. Furthermore heat pumps are seen as interesting partial upgrade of conventional fossil fuel-based energy systems in terms of energetic, economic and environmental benefits [12]. Moreover, when HPs are assessed from a Life Cycle Assessment method, interesting performance belong to them when compared to boiler solutions [13].

Nevertheless, the energy advantages associated with the electrification of the facilities tend to reduce with the increase in heat requirements [14]. It is clear that P2H, aiming at use all the available renewable electricity cannot meet in quantity, but above all, in quality the current heating demand. Especially, if this latter remains constant in mix due to the assumption that 85% of the 2050 building stock will be composed by existing buildings [15]. Looking at the slow trend of retrofitting interventions, the status quo will not be so diverse at that time. Therefore, High Temperature (HT) heating will still be part of the heating demand in the civil sector as well as in certain industrial processes.

Having said, accounting for limited gain in efficiency of HT Heat Pump compared to the investment costs for substituting well-proven fossil-fuel boilers a viable option is the Power-to-Gas strategy. Rather than changing the thermal machine, the electricity coming from renewables can be used to produce synthetic fuel to partially or fully substitute the existing supply [16]. Some of the authors already prove the beneficial effects deriving from Renewable Hydrogen production and addition to Natural Gas for greening the methane supply in Ref. [17]. Due to the fact that, where available, Natural Gas is the preferred supply along with the presence of its distribution infrastructures [18], those ones can be seen as a ready large-storage facilities to promote the renewable energy use. This concept has many demonstration projects documented in Ref. [19] as well as beneficial interactions with gas and carbon sector [20].

Indeed, Power to Gas was intended for solving both grid safety and balancing issues [21] as well as the stress in the distribution networks as proven by Robinius et al. [22], in the way of long-term energy carrier and storage [23]. Storage has a crucial role for robust energy planning in order to overcome the results of many research lines saying that without it solar and wind energy would play larger contributions only on yielding electricity [24]. The P2G allows merging the Electricity Grid to the Gas one with the conversion of electrical energy excess into a gas complying with the injection into it, as Hydrogen, at certain allowed volumetric fraction [25] or with further synthesis of this latter with Carbon Monoxide (CO) or Dioxide (CO_2) for producing methanol and methane [26]. Furthermore, hybridization with other processes such as air separation plants, bioenergy production, waste treatment and industrial processes have been widely studied and applied [27,28] up to large integration in National Energy systems such as for UK [29] and Spain [30]. In Countries, where NG Grid is not present or previous generation of biofuel propitiated the construction of methanol infrastructures, this other hydrocarbon can be considered a solution [31]. Yet, promising solutions can be scaled down to building level accounting for P2G as a link with transportation such as Hydrogen mobility and its energy interaction with the building energy system [32]. Recent review by Tronchin et al. [33] provides a suitable framework for the evolution of the built environment by the integration of storage options such as P2G. Indeed, Vialetto et al. [34] prove the techno-economic feasibility of energy interaction between a building and a hydrogen production and use by means of micro generation. The same concept was demonstrated for a Mediterranean climate with another energy system layout by the same authors [35]. Morevoer, Surgulu et al. [36] show further option of hydrogen integration for residential applications. Yet, the clear link to urban context was identified by few researchers such as Fischer et al. [37] who discussed about P2G role in the Smart Cities. A useful insight of the different scales of P2G application, urban scale included, is done by Eveloy et al. [38].

In this paper, the certain positive and high contribution of Heat Pumps to Medium Temperature and Low Temperature heating demand is coupled with Power-to-Hydrogen for methane blends to cover the HT heating demand. Therefore, a first implementation of P2H solution will be investigated in three reference Urban Energy Scenarios with different quality of demand, i.e. share of LT, MT and HT heating by means of electricity-based Heat pumps, and at increasing RES share in the energy system. Then, the combination of it with hybrid fuel based well-proven machines ready for handling Hydrogen enrichment, i.e. P2G solution, is considered. P2H & P2G was analysed to evaluate their interaction and the potential achievable benefits in terms of primary energy consumption of the whole energy system.

Research questions

The work investigated on Power-to-Gas and Power-to-Heat applications in the energy transition for urban scenarios towards Smart Urban Energy ones. Evaluating the contribution of viable P2G and P2H integration through established technologies aims at testing the benefits of coupling electricity and heating sectors in order to understand the viability of diverse renewable supply on the market, at the moment codified only in dispatch priority without any chance to use the stored excess. To do so, a crucial item is how to account for the diverse levels of temperature of available heating supply systems which call for dedicated thermal power production to meet the heating demand from quantitative and quality point of views. Afterward, the contemporary P2G and P2H technologies application was designed along with accounting for the possible leverage effect of their combination. The research questions this paper would address:

1. What well-proven electrical Heating Technology is applicable for improving energy efficiency as well as accounting for High, Medium and Low temperatures of energy demand?
2. What are pros and cons, as RES excess mitigation and Primary Energy Consumption, derived from P2G and P2H combined application with the aforementioned technologies at increasing Renewable Electricity Share?

Nevertheless other works dealt with heating distribution efficiency increase as well as its production such as District Heating [39], the authors focused on how to make more renewable supply of heat, through electricity-driven heating systems, in the case of P2H, and testing the effect of P2G addition through low-carbon H_2 hybrid fuels.

For this purpose, an overview of Electrical Heating Technologies (EHT) is provided in section High Temperature, Medium Temperature and Low Temperature Heating Supply by Electricity-driven Technologies. The energy system model the authors built in a previous study [17] is briefly presented. The analytical models of the EHT are explained in section Modelling heating supply technologies for implementing them into Urban Energy Systems. Then, in section Results and Discussion the discussion of the outcomes of EHTs implementation and their comprehensive combination at varying the RES share is done.

High temperature, Medium Temperature and Low Temperature heating supply by electricity-driven technologies

Temperature levels have to be taken into account for effective and efficient heating supply. Below, an overview of the technology options for heating purposes together with their cycle efficiency in achieving the highest temperature. Those details about the technologies allow to perform realistic energy scenarios.

CO_2 trans-critical HP technologies overview

A trans-critical vapour compression HP is an electric-driven machine which consists generally of an evaporator, a compressor, an expansion valve and a gas heat exchanger. Fig. 1 depicts a simplified layout with the main components and fluids loop [40]. Moreover, a temperature profile exists over the gas heat exchanger since at supercritical conditions no distinguishable phase change takes place as well as the latent heat value cannot be identified. Within the evaporator, the working fluid operates in subcritical conditions for CO_2, i.e. at temperature and pressure lower than 31.2 °C and 7.38 MPa, respectively. Therefore, the refrigerant undergoes a phase change.

This is why the trans-critical vapour compression HP is able to produce high temperature hot water either suitable for heating purposes or even for low pressure steam generation. In Refs. [40,41] the CO_2 HPs operating principle can be summarized:

- Saturated vapour at state 6 is firstly superheated to 1 and flows through the Internal Heat Exchanger (HEX);
- The gas pressure rises thanks to an electric compressor up to state 2 twice the lower one of the cycle to reach supercritical conditions;
- The supercritical CO_2 at state 2 is at high temperature (e.g. 130 °C). To discharge the thermal energy to the end-user is cooled down to state 3 by the gas cooler device.
- CO_2 at high pressure is again cooled down to state 4 in the Internal HEX economizing the heating up process and improving the efficiency.
- CO_2 is, then, expanded downstream the HEX through the expansion device to 5, i.e. the inlet thermodynamic condition to the evaporator. Lastly, the phase change occurs. Indeed, from 5 refrigerant state changes to 6 and evaporating it subtracts heat from the external fluid.

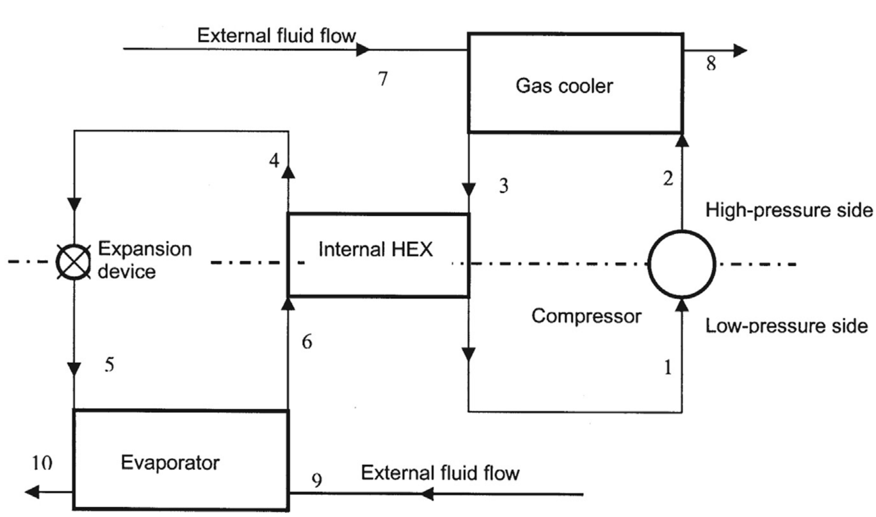

Fig. 1 – Layout of a transcritical CO_2 system. Source [40].

Furthermore, ideal cold heat sink can be river or ground water, ambient air or cooling water from engines. For instance, if installed nearby an existing refrigeration system or a power plant compressor or condenser those ones can be suitable sources.

In Table 1 the gas cooler temperature for several refrigerants to trans-critical cycle were reported with varying the supply water temperature from 80 °C up to 120 °C, assuming the evaporator temperature equal to 20 °C. That entails the possibility to use an energy carrier at 40 °C as driving source. According to Chua et al. [43], those HPs can be fruitfully applied in Power to Heat applications combined to CHPs to improve the overall system efficiency along with mitigating the drawbacks of renewables intermittency as proven by Blarke [44].

Two-stage electric HP technologies overview

A Two stage and multistage heat pumps belong to EHPs typology. Their application is interesting especially for heating production at high temperature level in all those places where the climate conditions are defined severe. They are categorized as compound or cascade systems [45], depicted by Fig. 2. On the market also as reversible machine for both cooling and heating are available. A compound system is a serial connection of two or more compression stages to obtain a multi-pressure working fluid. In comparison with the single-stage HP, the multi-stage one is usually characterized by lower compression ratio but, for each stage of compression higher efficiency, larger refrigeration effect and flexibility, and lower temperature of discharge in the high-stage compressor [46,47].

To reach higher Coefficient Of Performance values, the so-called inter-stage pressure is often fixed with the aim at equally splitting, where possible, the total compression ratio [47]. The authors of [48] carried out an experimental campaign to evaluate the energy performance of one two-stage HP using CO_2 refrigerant for cold districts in Japan for domestic hot water production. From the study it emerged that the ratio of low to high pressure, the compressor suction to the discharge,

Table 1 – Gas cooler temperature for each refrigerant with changes in discharging temperature [41,42].

	R744	R143	R236ea	R236fa	E134	R114	R141b/R22
T_{dis80}	90.48	118.60	85.44	96.24	107.50	97.52	106.40
T_{dis100}	107.20	140.10	114.40	112.50	127.20	116.00	132.80
T_{dis120}	125.30	158.70	129.30	125.10	144.20	131.30	153.90

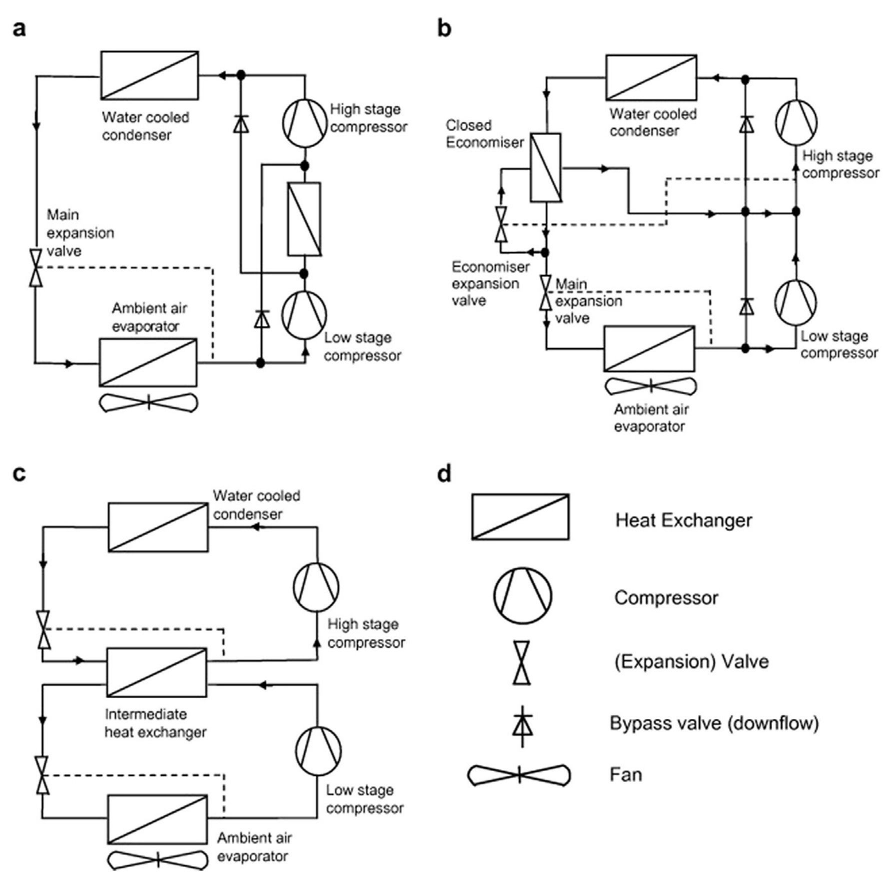

Fig. 2 – Layouts of the two-stage HP with intercooler (a), two-stage HP with closed economizer (b), cascade or series cycle (c), legend (d). Source: [48].

respectively, was high and it affected the operation of the compressor in all those regions where the coldest temperatures drop down to -10/-20 °C. Subsequently, a decrease was found in the water heating capacity and the COP value as well. The technical solution to overcome those setbacks and to improve the HP reliability was the strategy of dividing the gas pressurization phase into two different steps together with the injection of the refrigerant in an intermediate pressure [48]. Hence, a compound multi-staging HPs system is a viable layout for efficient heating end–users located in severe climate areas. Differently, two independently operated single-stage refrigeration systems constitute a cascade system: the first one works at low pressure to maintain lower evaporating temperature, while the second one works at a higher evaporating temperature, depicted in Fig. 2c [45]. Combining those systems is done by a new built-in component, able to exchange heat from bottom cycle to the topping one and to work, at the same time, as a condenser and an evaporator. In Ref. [49] the potential of a heating system equipped with a double-stage HP is investigated. Furthermore, an air source was coupled to the lower pressure cycle and a water source to high pressure one. In comparison with other heating systems, the aforementioned layout guarantees an energy efficiency ratio higher by 20% [49]. Nevertheless, the great part of the HP systems available on the market still comprise the single stage vapour compression cycle since they are considered the most reliable solution.

Methods

This work accounts for building different energy generation layouts to deliver heat. Heating demand to be met is characterized by different temperatures. Two strategies were adopted: Power-to-Heat and Power-to-Gas. Their application and their combination effects were assessed in terms of changes in PEC, efficiency of the overall layout, fraction of renewability on the energy supplied and highlighting the specific target of the Renewable Heat delivered by the system. For this purpose, an aggregated model, previously proposed by Nastasi et al. [17], was adopted to compute the normalized energy consumed to meet the electricity and heating demand of the system. Heating demand is, therefore, converted in one hundred dimensionless units and it is investigated accounting for the three temperatures of delivery (HT/MT/LT), as depicted by Fig. 3.

The focus of the study is the interaction between RES and heat delivery, switching the supply from fuel-based to electricity-based, specifically renewable electricity in the transition scenarios assuming a Power Grid efficiency equal to 42% as forecasted in 2030 in Ref. [50].

Reference model

Fig. 3 shows the established thermal energy systems for HT, MT and LT levels. Fuel to Heat process is the kind of the first temperature and Fuel to Heat and Electricity for the second temperature by means of CHP. While, Electricity to Heat process is the third temperature level.

To model the energy system Equations from 1 to 13 were reported. As regards the HT level, the Heat Demand is supplied by CHP thermal output along with the Boiler assistance.

$$E_{D,H(HT)} = E_{H,CHP} + E_{H,Boiler} \tag{1}$$

The following equation describes the associated PEC $E_{fuel,sys(HT)}$:

$$E_{fuel,sys(HT)} = \frac{E_{Grid}(HT)}{\eta_{el,Grid}} + E_{fuel,CHP} + E_{fuel,Boiler} \tag{2}$$

Moreover, for the Medium Temperature End-User, the Heat Demand is supplied by the Absorption Gas Heat Pump (AGHP) along with the Condensing Boiler.

$$E_{D,H(MT)} = E_{H,AGHP} + E_{H,Cond.\ Boiler} \tag{3}$$

Eq. (4) reports the associated PEC $E_{fuel,sys(MT)}$:

$$E_{fuel,sys(MT)} = \frac{E_{Grid(MT)}}{\eta_{el,Grid}} + E_{fuel,AGHP} + E_{fuel,Cond.\ Boiler} \tag{4}$$

The HP meets the low temperature demand.

$$E_{D,H(LT)} = E_{H,HP} \tag{5}$$

Then, Eq. (6) describes the LT PEC $E_{fuel,sys(LT)}$:

$$E_{fuel,sys(LT)} = \frac{E_{Grid(LT)}}{\eta_{el,Grid}} \tag{6}$$

To conclude, overall PEC of the system is the sum of all LT, MT and HT PECs and reads as:

$$E_{fuel,sys(TOT)} = \sum_{j=1}^{N} E_{fuel,sys(j)} \tag{7}$$

Eq. (8) defines the renewable electricity excess E_{REX} when its share is higher than 25% value.

$$E_{REX} = R_{res} \cdot \sum_{j=1}^{N} E_{el,RES(j)} \tag{8}$$

Furthermore, the renewable fraction of electricity, f_{RES}, can be calculated as the ratio between $E_{el,RES}$ and the electricity users. In the reference case, they are composed by the scenario Electricity Demand and the Heat Pump feeding.

$$f_{RES} = \frac{\sum_{j=1}^{N} E_{el,RES(j)}}{\sum_{j=1}^{N} E_{D,el(j)} + E_{el,HP}} \tag{9}$$

For the comprehensive fraction of renewable energy, Eq. (10) describes F_{RES}:

$$F_{RES} = \frac{\sum_{j=1}^{N} E_{el,RES(j)} + E_{h,RES(j)}}{\sum_{j=1}^{N} E_{D,el(j)} + E_{D,h(j)}} \tag{10}$$

In the model, Eq. (11) introduces a constraint related to the fixed fuel needed by the CHP independently of its electricity production, i.e. its efficiency.

$$\frac{d\left(E_{fuel,sys(TOT)}\right)}{d\left(E_{el,\ CHP}\right)} = 0 \tag{11}$$

As regards the Demand, the Power To Heat Ratio (PTHR) is reported in Eq. (12).

$$PTHR = \frac{E_{el,D}}{E_{h,D}} \tag{12}$$

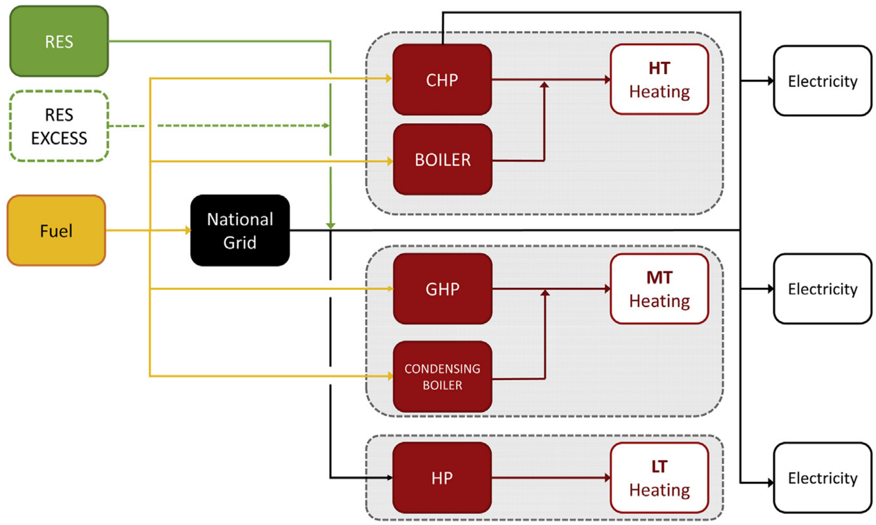

Fig. 3 – Aggregated model of the Urban Energy System considering established energy producers for meeting the diverse heating temperatures [17].

To investigate on thermal energy, the total request for Heating has been normalized. Indeed, the following Equation shows 100 dimensionless units:

$$E_{D,H(HT)} + E_{D,H(MT)} + E_{D,H(LT)} = 100 \quad (13)$$

Therefore, each Electricity demand calls for a relative Temperature level proportionally to the Power To Heat Ratio of the analysed Urban Model.

Table 2 reports the calculations made for the Reference Scenarios with a RES share of 25% and a RES excess equal to 0, as in Ref. [17].

The three Urban Energy Systems show the Power-To-Heat Ratio value ranging between 0.13 and 0.283. Diverse PTHR correspond also to different composition of the heating demand in terms of required temperature supply. For instance, RM case has a heating demand mainly composed by HT request, i.e. 70% versus 20% of MT and 10% of LT one. As identified by Nastasi et al. [17], the system described by the PTHR was used as model of reference Urban Energy Systems characterized by this quality of heating demand. In other words, this latter describes the typology of end-users which is equal to the kind of building stock and its energy performance. This process was done by checking the EPISCOPE/TABULA database [51] to account for heating generation and distribution system nature along with the temperature level of the installed HVAC apparatus. The logic of the proposed model is to first satisfy the lowest energy-intensive demand to reach the lowest primary energy consumption. For instance, the Low Temperature supply due to its high Coefficient of Performance will play a key role.

Modelling heating supply technologies for implementing them into Urban Energy Systems

The current increase of electric renewables implies that higher values of PTHR offer much more chance for renewable integration. Here, the electricity-driven machines for heating supply were considered.

Therefore, two strategies were elaborated and their impact on the energy system was measured by the calculation of the obtained savings in primary energy consumption and the change in the fraction of integrated renewable energy both in the heating supply and the heating and electricity sectors. The implemented strategies are:

- P2H - Power-to-Heat by harvesting the renewable electricity excess for feeding electrical heaters;
- P2H & P2G - Power-to-Heat and Power-to-Gas and combined to test the interaction.

Therefore, the Equations for the strategies' implementation were presented below together with highlighting in bold the new introduced terms in the Equations of the overall energy system perfomance.

P2H power to heat integration

The electricity excess is now considered to feed electricity-based heating solutions. Compared to the reference energy system in Fig. 3, the P2H integration implies the addition of further heat generators. At High Temperature a Trans-critical CO_2 Heat Pump is proposed since it is the most common HT electricity-based solution already available on the market. It will use the CHP heat excess as cold heat sink. At Medium Temperature, a two-stage Heat Pump is the selected new technology with an internal double cycle able to provide heat most efficiently of a Condensing Boiler. As regards each HP option, the Coefficient Of Performance COP is defined as:

Table 2 – Parameters for the Reference Energy Scenarios and temperature levels demands.

Urban system	PTHR	PEC	RES share	$E_{el,tot}$	H_{HT}	H_{MT}	H_{LT}
RM	0.13	108.7	7.9	13	70	20	10
BER	0.189	104.6	5.4	18.9	40	50	10
KPH	0.283	110.5	9.9	28.3	20	40	40

$$COP = \frac{E_{h,HP}}{E_{el,HP}} \tag{14}$$

where $E_{h,HP}$ is the thermal energy output and $E_{el,HP}$ is the electrical energy consumption. The HT is able to harvest the CHP heat waste $E_{waste,CHP}$ as defined in Eq. (15) and to use it with an effectiveness ε as reported in Eq. (16).

$$E_{waste,\ CHP} = (1 - \eta_{el,CHP} - \eta_{hr,CHP}) \cdot E_{fuel,CHP} \tag{15}$$

$$E_{waste,\ CHP} \cdot \varepsilon = E_{in,HP(CO2)} \tag{16}$$

Then, the heating supplied by CO_2 –HP reads as:

$$E_{H,\ HP(CO2)} = \frac{E_{in,HP(CO2)}}{\left(1 - \frac{1}{COP_{HP(CO2)}}\right)} \tag{17}$$

Its electricity demand $E_{el,HP(CO2)}$ is calculated below:

$$E_{el,\ HP(CO2)} = \frac{E_{H,HP(CO2)}}{COP_{HP(CO2)}} \tag{18}$$

Referring to the two-stage HP, its heating supply $E_{H,HP(2s)}$ is shown in Eq. (19) as well as its electricity demand in the subsequent one.

$$E_{H,HP(2s)} = f_{HP} \cdot E_{D,H(MT)} \tag{19}$$

$$E_{el,\ HP(2s)} = \frac{E_{H,HP(HT)}}{COP_{HP(HT)}} \tag{20}$$

From the implementation of the previous equations, the electricity demand at each temperature level is re-written by introducing the associated new terms:

$$E_{D,el(HT)} + E_{el,exc(HT)} + \mathbf{E}_{el,\ HP(CO2)} = E_{Grid(HT)} + E_{el,RES(HT)} + E_{el,\ CHP} \tag{21}$$

$$E_{D,el(MT)} + E_{el,exc(MT)} + \mathbf{E}_{el,\ HP(2s)} = E_{Grid(MT)} + E_{el,exc(HT)} + E_{el,RES(MT)} \tag{22}$$

$$E_{D,el(LT)} + E_{el,HP} = E_{Grid(LT)} + E_{el,exc(MT)} + E_{el,RES(LT)} \tag{23}$$

Similarly, the heat balance at HT and MT reads as:

$$E_{D,H(HT)} = E_{H,CHP} + E_{H,Boiler} + \mathbf{E}_{H,HP(CO2)} \tag{24}$$

$$E_{D,H(MT)} = E_{H,AGHP} + \mathbf{E}_{H,HP(2s)} \tag{25}$$

$$E_{D,H(LT)} = E_{H,HP} \tag{26}$$

It is clear that the condensing boiler is not competitive with the 2s-HP. In the reference energy systems both Boiler and Condensing Boiler played the role of backup as in reality. Here, they represent the fraction of end-user where this technology could not be easily substituted due to refurbishment constraints or economic barriers.

Fig. 4 depicts the layout of the energy system with integrated P2H option.

P2G & P2H Power to Gas and Power to heat combined integration

The last analytical expressions are related to the integration of both P2G and P2H. To do so, first of all, some limit has to be assumed. For instance, since the renewable electricity excess will meet electric needs of electrolyser in P2G and new electricity-driven HP in P2H, a specific Hydrogen energy $E_{H2,limit}$ is defined as:

$$E_{H2} = ES_{H2,limit} \cdot (E_{fuel,CHP} + E_{fuel,AGHP} + E_{fuel,Boiler}) \tag{27}$$

Then, the aformentioned proportion between electricity is shown below:

$$E_{el,RES(TOT)} = \sum_{j=1}^{N} E_{el,RES(H2j)} = \sum_{j=1}^{N} E_{el,RES(j)} + f_{RES} \cdot E_{el,ELY(j)} \tag{28}$$

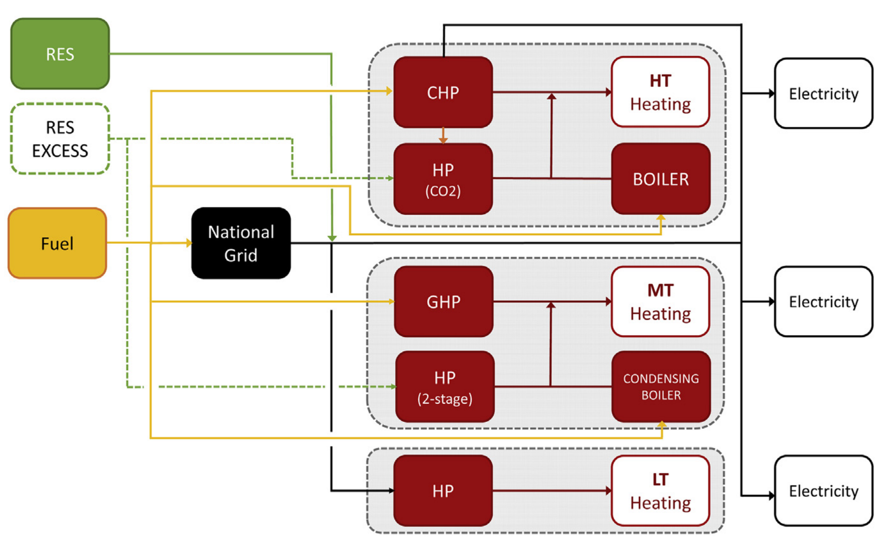

Fig. 4 – Aggregated model of the Urban Energy System considering established and electricity-based heating technologies for meeting the diverse heating temperatures by Power-to-Heat integration.

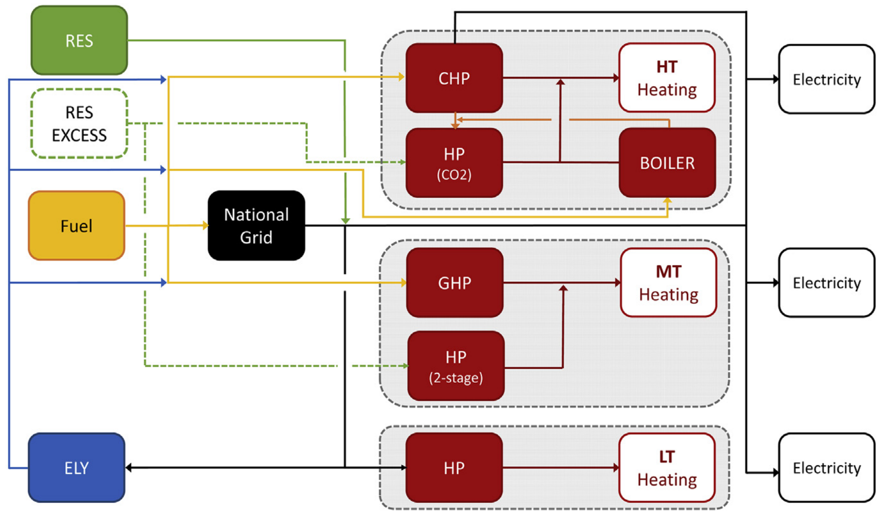

Fig. 5 – Aggregated model of the Urban Energy System considering established and electricity-based heating technologies for meeting the diverse heating temperatures by the combination of Power-to-Gas & Power-to-Heat integration.

The CO2-HP will be able to use the heat wasted from CHP and Boiler as cold heat sink by Eq. (29):

$$\left(E_{waste,\ CHP} + E_{waste,\ Boiler}\right) \bullet \varepsilon = E_{in,HP(CO2)} \tag{29}$$

The use of the combination P2G & P2H entails the following electric balance at each temperature level:

$$E_{D,el(HT)} + E_{el,exc(HT)} + \mathbf{E}_{\mathbf{el},\ \mathbf{ELY(HT)}} + \mathbf{E}_{\mathbf{el},\ \mathbf{HP(CO2)}} = E_{Grid(HT)} + E_{el,RES(HT)} + E_{el,\ CHP} \tag{30}$$

where $E_{el,HP(CO2)}$ represents the electricity demand of the HT CO_2-Heat Pump.

$$E_{D,el(MT)} + E_{el,exc(MT)} + \mathbf{E}_{\mathbf{el},\ \mathbf{ELY(MT)}} + \mathbf{E}_{\mathbf{el},\ \mathbf{HP(2s)}} = E_{Grid(MT)} + E_{el,exc(HT)} + E_{el,RES(H2,MT)} \tag{31}$$

where $E_{el,HP(2s)}$ represents the electricity demand of the MT electric Heat Pump.

$$E_{D,el(LT)} + E_{el,HP} + \mathbf{E}_{\mathbf{el},\ \mathbf{ELY(LT)}} = E_{Grid(LT)} + E_{el,exc(MT)} + E_{el,RES(LT)} \tag{32}$$

The Heat Balance is the same of the P2H case as previously reported in Eqs. (24)–(26).

$$E_{fuel,sys(TOT)} = \sum_{j=1}^{N} E_{fuel,sys(j)} - \mathbf{E}_{\mathbf{H2}} \tag{33}$$

The combined P2G & P2H integration scenario is represented in Fig. 5. Moreover, The introduced electrolyser has an efficiency of 0.65 based on the Low Heating Value (LHV) of Hydrogen.

Results and discussion

Here, the results of the simulations performed by the authors are presented and discussed in order to fill the gap in the research identified in Research Questions. The outcomes were computed through an optmization process for minimizing the PEC. To summarize, two technology layouts, i.e. P2H and its combination with P2G, were considered with varying the RES share by 25%, 30%, 40% and 50% so as to build twenty four scenarios, eight for each Urban Energy System. Furthermore, the delivered Renewable Heat value has been calculated for the aforementioned scenarios. Table 3 outlines the values of technological parameters for performing energy scenarios simulation.

In detail, High Temperature entails a supply around 85 °C, as in the case of conventional boilers. Medium Temperature belongs to 65 °C and it is the case of Gas Engine Heat Pump or for the Domestic Hot Water production. While, Low Temperature space heating is about 45 °C as representative value for heat provided by electric Heat Pumps. The P2H and its combination with P2G together with their detailed layouts are explained in P2G & P2H-based Energy Scenarios with changes in RES share of 30% - 40% - 50%. Moreover, the increasing RES share from 25% to 50% was included. The extreme values are the current average RES penetration in the energy systems of Developed Countries and the foreseeable RES share target of 2050 roadmaps, respectively.

P2H-based energy scenarios with changes in RES share of 30%–40% - 50%

The first analyzed strategy is the Power-to-Heat. As presented in P2H Power to Heat integration, the HT and MT heating systems were enriched by electrical machines for shifting to Electricity-to-Heat solution. Since the aim is to effectively integrate the RES electricity excess so that to increase the RES share, this fuelling shift moves towards Renewable-to-Heat options. In details, a CO_2 Heat Pump will convert the RES electricity excess into HT heat harvesting part of the CHP thermal output as cold heat sink.

As regards the MT supply, double-stage Heat Pumps were installed feeded by aerothermic source as the cold heat sink. While, the LT solution remained the same since it was already chosen as air-to-air electric HPs. The electrification process applied to thermal energy production entails a reduction in

Table 3 – Performance Values of High, Medium and Low Temperature technological solutions.

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
	HP_{CO2}	**COP_{HPCO2}**	**3**
MT	COND. BOILER	η_h	1.05
	GHP	COP_{GHP}	1.4
	HP 2s	**COP_{HP2s}**	**2**
LT	**HP**	**COP_{HP}**	**3.5**

PEC in the RM and BER layouts which show a fuel demand variation from 108.7 and 106 to 97.8 and 95.2, respectively. Since those scenarios were composed by 90% of non-LT supply, a decrease of more than 10 fuel units was found for both of them. Furthermore, considering that, given a fixed heat sink, the lower the temperature supplied the higher the electricity-driven heating system performance, the RES share increase up to 50% provided further gains by reducing the fuel demand to 91.89 in RM case and to 81.66 in Berlin case. This is due to the highest share of MT supply in the BER case compared to the RM one along with an absolute reduction of 14 fuel units compared to 6 ones. At RES share value of 25%, the KPH scenario with P2H integrated shows the PEC equal to the one without it, i.e. 110.58, while at 50% the fuel demand decreases drammatically to 82.57 units. So, 25% more of RES share caused more than 30 avoided fuel demand units. This strong change is due to the fact that when HT and MT were partially substituted with electricity-driven solutions, no gains are possible since the RES is already meeting all the LT demand without the opportunity to go further in greening the other temperature level supplies. So, further electricity demand must be compensated by the Grid which requires new fuel demand based on its conversion efficiency. When the RES share rises to 50%, it is possible to integrate much more renewable energy in absolute value. As shown in Fig. 6, the right-side axis reported the RES fraction of the total energy demand. In the BER case 50% of RES share implies about the same percentage of the total RES fraction, while in the KPH case with the same RES share it is possible to overcome the 70% of renewable faction on the entire energy system. A lower RES fraction increase corresponds to the RM scenario with 50% of RES share, about 14% points. This is caused by a strong dependency on fossil fuel based solutions for HT which is great part of the heating demand. From that, it would be clear that imposing the same Renewable Energy Share into the National Power Grid of various Countries entails different actual renewability ratio in the energy mix as well as on the cross-sector heating and electricity systems.

For this reason, since the aim of the study is to analyze the transition to Electrified Heating, the authors considered of primary importance to analyze the Renewable Heat (RH) delivered in the built energy scenarios as depicted in Fig. 7. In all the scenarios, doubling the RES share with the P2H integration corresponds to doubling the renewable heat fraction which increase from 6.55% to 12.43%, from 8.31% to 16.13%, and from 14.03% to 28.06% for RM, BER and KPH, respectively. The best performance in absolute value belongs to the KPH. Its renewable heating fraction at 50%of RES share is more than twice of the RM case at the same conditions. Furthermore, KPH reference scenario already shows a RH fraction higher than all the RM and BER scenarios at different RES share. It is noteworthy that the only P2H application leave the heating sector strongly dependent on the fossil fuels. As a matter of fact the remaining electricity demand is supplied by the Power Grid which, depending on the National energy policy and subsequent energy business models [52], is characterized by a fluctuating Primary Energy Fraction (PEF) value during the year [53] and still mainly composed by fossil fuel-base generation.

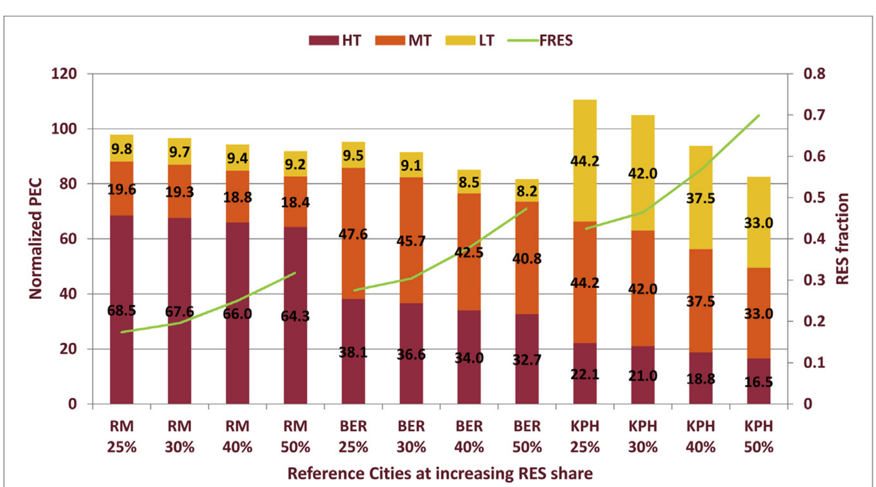

Fig. 6 – Normalized PEC and RES fraction of P2H application to Urban Energy Systems with changes in RES share.

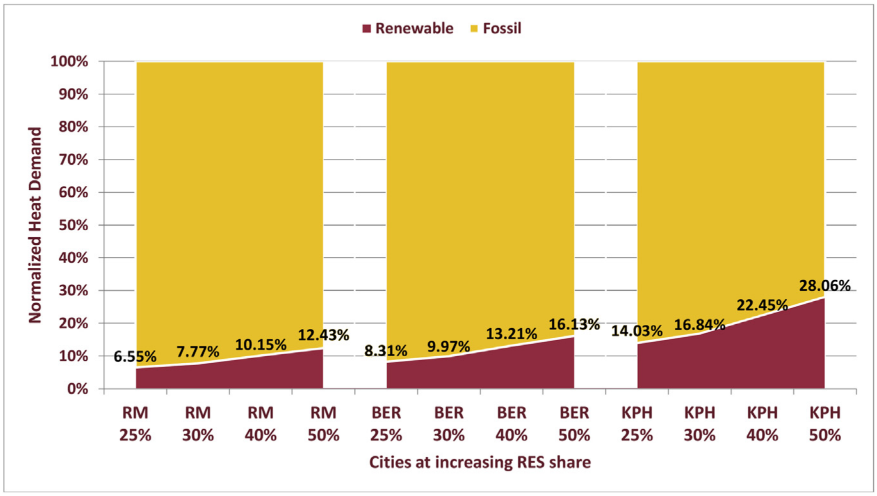

Fig. 7 – Normalized Renewable and Fossil Heat Demand of P2H application to Urban Energy Systems with changes in RES share.

P2G & P2H-based energy scenarios with changes in RES share of 30%–40% - 50%

From the analysis of the first technological option, it emerges that P2H provides considerable gains in PEC and, above all, in terms of renewable fraction of the total energy demand, i.e. electricity + heat. While, P2G application does not provide PEC savings compared to the BAU scenarios in Urban Energy Systems [17]. The only beneficial contribution is given to the amount of deliverable Renewable Heat. That value is lower than the one in P2H case for RM and BER at each RES share, whereas it is higher than the ones in P2H for KPH at each RES share. This interesting result for the high PTHR Urban Model provides the motivation to investigate on the combination of both technologies. The thesis is that the interaction in P2G & P2H combined scenarios would receive benefit from a leverage effect of their contemporary application giving a total gain higher than the simple addition of gains shown in the previous subsection and in the previous study in Ref. [17].

Fig. 8 shows that the combination of P2G & P2H as renewable capacity firming solutions implies high RES fraction on the total energy demand. At 50% RES share, more than half of the overall energy demand becomes renewable in all the Reference Urban Model. The higher the Urban model PTHR, the more inclined the RES fraction trend. The lowest Normalized PEC belongs to the BER case at 50% RES share. At low RES shares equal to 25% and 30%, RM case shows the best performance since the amount of integrated renewable electricity production is directly used to substitute the Grid supply along with its fuel consumption and not dedicated for greening the heating supply.

On the contrary, for high PTHR where MT and LT heating solutions are the main thermal energy providers, the renewable electricity excess in converted more effectively in renewable heat. A first statement is that current energy systems with high share of HT heating demand are able to integrate the combined P2G & P2H solutions in the largest PEC savings due to the high integration of electric renewables in

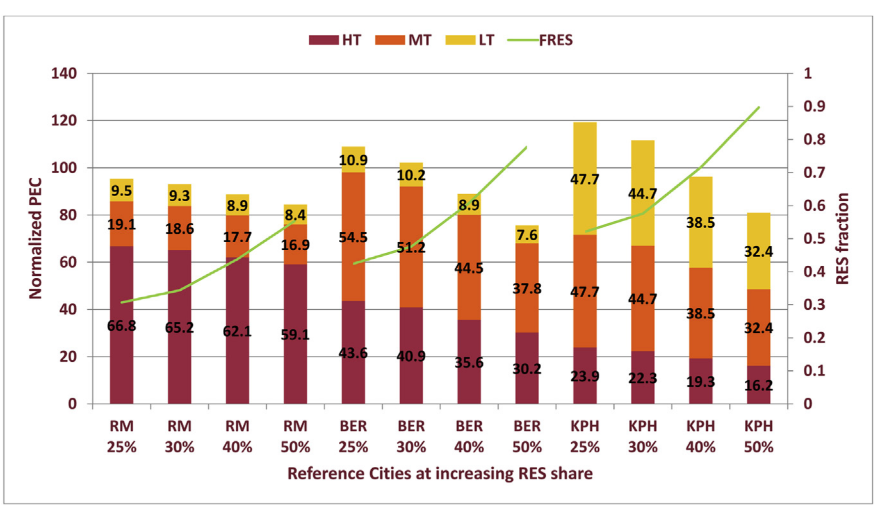

Fig. 8 – Normalized PEC and RES fraction of P2H & P2G application to Urban Energy Systems with changes in RES share.

the system. Yet, this quality of heating demand results not suitable when the RES share overcomes the 30% value since they are not capable to integrate efficiently further electric renewables. Building stock retrofitting towards decreasing the temperature of heating supply could play a key role to convert much higher amount of electric renewables into total renewable fraction on electricity + heat sectors.

Furthermore, it is remarkable that the demonstrated suitability of low PTHR scenarios for immediate PEC benefits at low RES share does not allow the heat and electricity merging, a foreseeable synergy to handle the energy transition. In other words, the synergy will take place by a more rational use of energy in order to meet the demand more efficiently in terms of energy expenditures and more effectively matching the time of demand and production thanks to inter-sectorial links. As aforesaid, a big challenge is the energy retrofitting strategy composed by energy efficiency measures and, above all, lowering the heating temperature supply along with its technical adjustments. For instance, those latters consist of substituting the heating producer from boiler to condensing one as well as the heating terminals which must be sized bigger to guarantee the same delivered heat.

This operation should take into account the architectural constraints belonging to existing and historic buildings which are actually the HT end-users. Therefore, a massive retrofitting strategy needs a careful survey of the building stock and its features.

Fig. 9 reports that the higher the RES share the higher the system efficiency is. The slope of the trends is greater after the 30% RES share value. The highest η_{sys} belongs to BER and KPH scenarios with the maximum RES share. Indeed, for low RES share BER and KPH scenarios have lower η_{sys} than the RM one.

On the other hand, after 30% this parameter grows dramatically providing the advice to go for lower temperature levels as an effective efficiency measure. Indeed, EU targets directly address the decarbonization of the sector without a clear threshold for the renewable heating & cooling. Only, the recent Renewable Heating & Cooling initiative [54] translated

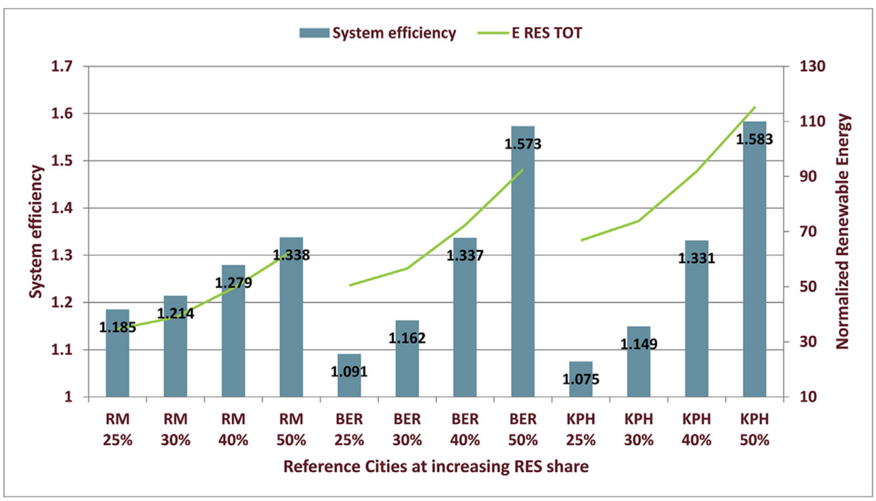

Fig. 9 – System efficiency and Normalized Renewable Energy of P2H & P2G application to Urban Energy Systems with changes in RES share.

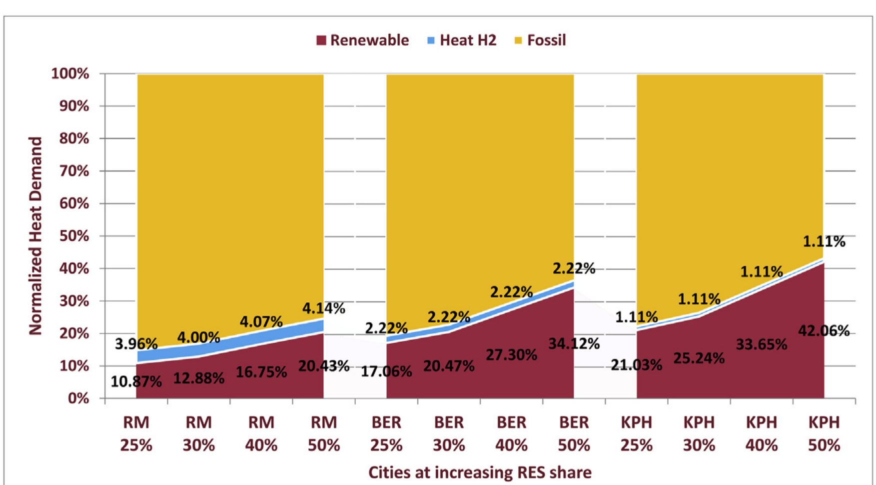

Fig. 10 – Normalized Renewable, H2-based and Fossil Heat Demand of P2H & P2G application to Urban Energy Systems with changes in RES share.

the decarbonization objectives in a foreseeable 20% of renewable energy supply for the aforementioned sector. The results of the technologies studied in this paper overcome this value of renewable supply making P2G and P2H promising solutions in the transition scenarios.

From Fig. 10, it emerges that the combination P2G & P2H implies the highest values of Renewable Heat as well as the Renewable Energy fraction. In RM case at 50% of RES share, the value is 24.57%, twice the one for the only P2H application at same RES share which is equal to 12.43% and three times the one for the only P2G application which is equal to 8.39%. Moreover, the combined system scenario gives a performance even 3.75% higher than the sum of the renewable heat deliverable in the separated P2G and P2H solutions.

Referring to BER scenarios, the highest Renewable Heat amount is 36.34%. It is 10.91% greater than the sum of only P2G plus only P2H application, which are 9.30% and 16.13%, respectively. In KPH scenario that phenomenon does not happen. The combined solutions still provide higher Renewable heat fraction with 43.17% compared to 30.59% and 28.06%, which belong to the single P2G and P2H technology adoption, respectively.

It is worth noting that P2G is similar to the combined system since the RES share, as in the only P2H scenario, covers all the electrical demand of LT heating systems but, it is able to further provide beneficial effects by the fuel substitution in MT and HT fuel-based heating technologies.

Therefore, it can be stated that Power-to-Gas plays an unlocking role for further increase of renewability and PEC savings when combined to Power-to-Heat application.

Conclusions

The authors wanted to test the opportunity to meet the HT heating demand with conventional fuel-based technologies fed by renewable Hydrogen supply in combination with electric-based Heat Pumps. In the energy transition scenario, the building stock still requiring HT supply is not negligible. This attempt was made by twenty four energy scenarios by varying the Renewable Electricity Source share and adopting electrical heat pumps for supplying heat at HT, MT and LT temperature. This analysis was performed by an aggregated model of three Reference Urban Energy Systems. It was a parametric analysis of the all Normalized Energy Demand portfolios to assess Primary Energy Consumption, System efficiency, the fraction of Renewable Energy in the system and, specifically, the share of Renewable Heat delivered.

The concluding remarks are:

- To modernize and make more efficient the HT and MT heat delivery, electrical machines were used as a Power-to-Heat strategy shifting from Fuel-to-Heat to Electricity-to-Heat solution. Since the aim is to effectively integrate the RES electricity excess so that to increase the RES share, this fuelling shift moves towards Renewable-to-Heat options.
- The objective function of minimum Primary Energy Consumption was set to optimize the model. The authors analysed three reference Urban Energy Models and their Primary Energy Consumption were computed at increasing RES share: 25%, 30%, 40% and 50%.
- Two analytical models for P2H and P2G & P2H were designed and integrated into the reference Urban Energy Systems. The first calls for an electrification of the heating suppliers by means of different typologies of Heat Pumps at the diverse temperature levels. Its interaction with P2G implies the electrolysers' installations to produce Hydrogen by renewable electricity excess.
- In the P2H scenario, doubling the RES share with the P2H integration corresponds to doubling the Renewable Heat fraction which increases from 6.55% to 12.43%, from 8.31% to 16.13%, and from 14.03% to 28.06% for RM, BER and KPH, respectively.
- In the P2G & P2H scenario, the interaction provides benefits from a leverage effect of their contemporary application giving a total gain higher than the simple addition of the single gains in RM and BER cases, while in KPH one the high share of LT demand have already enhanced the effect of the only P2G application.
- It is expected that when mobility sector will be driven by policy and incentive schemes towards electrification, the renewable electricity excess would be systematically reduced thanks this further inter-sectorial link.

Finally, it deserves being noticed that:

Renewable Power-to-Hydrogen enables the Power-to-Heat application more effectively contributing with a decarbonizing effect due to the partial substitution of NG with H_2 in the fuel feeding for HT & MT, in addition to the greening effect on the electricity demand already given by P2H. Indeed, combined P2G&P2H promotes contemporary the NG greening, the inter-sectorial link between heat with electricity sectors at RES share increase.

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