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The Potential of Hydrogen Enriched Natural Gas deriving from Power-to-Gas option in Building Energy Retrofitting

Livio de Santoli[a], Gianluigi Lo Basso[a,*], Benedetto Nastasi[b]

[a] Department of Astronautics, Electrical and Energy Engineering (DIAEE), Sapienza University of Rome, Via Eudossiana 18, 00184 Rome, Italy
[b] Department of Architectural Engineering and Technology (AE+T), Environmental & Computational Design Section, TU Delft University of Technology, Julianalaan 134, 2628 BL Delft, The Netherlands

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ABSTRACT

This paper deals with the role of Hydrogen enriched Natural Gas (H2NG) in Hybrid Energy Systems for energy refurbishment purposes. In detail, three different plant layout options were investigated. A photovoltaics (PV) array and two-stage electric heat pump (EHP), a hybrid photovoltaic thermal solar collectors combined to gas heat pump (GHP) fuelled with H2NG, and a CHP fuelled with H2NG connected to a two-stage EHP were compared. The required receiving surfaces of PV array were estimated for three different direct normal irradiation (DNI) values in Italy in order to assess how the available roof surface affects the layout choice. A sensitivity analysis was carried out with varying the building power to heat ratio (PTHR) and the hydrogen volumetric fraction in the H2NG mixtures to assess the primary energy consumption (PEC) and renewable energy fraction. When feasible, the PV + EHP shows the best performance in terms of PEC with a solar energy share equal to 65%. In other cases, the PV/T + GHP fuelled with H2NG @30%vol. can be suitable for PTHR higher than 0.2 approximately. Furthermore, the third layout CHP + EHP is not competitive with the other solutions but, it is the best option where no roof surfaces are available for PV or PV/T installation.

1. Introduction

Rational energy utilization is still the aim of most policy interventions in the building sector along with the technical ones to reduce the energy demand towards the nZEB [1]. Renewable energy deployment is becoming an energy efficiency tool for building stock [2] accounting for landscaping impacts [3], connections with territorial well-established economics and effective use of available resources [4]. In recent years, research technological solutions for sustainable energy purposes, such as combined heat and power (CHP) system, electric heat pump (EHP) and photovoltaics (PV) have been widely investigated [5–7]. Yet, existing buildings greening is the main environmental and economic challenge due to their amount and their relative constraints as well as the required inter-disciplinarity approach [8]. Indeed, promising solutions such as PV + EHP are immediately feasible in new low energy buildings while, they are not suitable to be installed in the current built environment. So, alternative solutions related to the energy production should be taken into account to overcome such limits [9]. Hydrogen application at building scale received strong attention for dwellings located in Mediterranean and Northern Europe climate [10,11]. But, it is remarkable that those pioneer projects are related only to new buildings. To manage the transition for the existing ones, the eco-fuels use appears as foreseeable in order to reduce carbon dioxide emissions, directly [12,13]. In this framework, the hydrogen enriched natural gas blends are a viable option to feed current energy production devices and to mitigate the renewables capacity firming issues of the power grid [14,15]. Indeed, the so-called power-to-gas is able to convert the RES electricity excess into renewable hydrogen to be injected into the natural gas pipelines [16,17]. This power shifting way could be used to enhance the supply renewability in existing building stock. Indeed, this latter is composed by dwellings built after the Second World War to be renovated and cultural heritage or listed historic buildings to be preserved and make comfortable for modern use. The key driver of this study is to introduce renewable energy supply by means of Hybrid Systems as well as local production from solar energy. Where PV or PV/T cannot be installed on roof surface due to architectural and technical constraints, the power-to-gas scenario consisting of renewable hydrogen injected to NG pipelines is

* Corresponding author.
E-mail addresses: livio.desantoli@uniroma1.it (L. de Santoli), gianluigi.lobasso@uniroma1.it, ing.gianluigi.lobasso@gmail.com (G. Lo Basso), b.nastasi@tudelft.nl, benedetto.nastasi@outlook.com (B. Nastasi).

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Nomenclature

COP_{GHP}	coefficient of performance of gas heat pump
$E_{D,el}$	building electricity demand
$E_{D,H}$	building thermal energy demand
$E_{el,CHP}$	combined heat and power electricity production
$E_{el,EH}$	electrical heater electricity need
$E_{el,HP}$	heat pump electricity need
$E_{el,PV}$	photovoltaics electricity production
$E_{el,PV/T}$	hybrid solar collectors electricity production
$E_{fuel,CHP}$	combined heat and power primary energy need
$E_{fuel,GHP}$	adsorption gas heat pump primary energy need
$E_{fuel,sys}$	hybrid energy system primary energy need
E_{Grid}	electricity provided by the national grid
$E_{H,CHP}$	combined heat and power heat production
$E_{H,EH}$	electrical heater heat production
$E_{H,GHP}$	adsorption gas heat pump heat production
$E_{H,HP}$	heat pump heat production
$E_{H,PV/T}$	hybrid solar collectors heat production
E_{H2}	hydrogen energy
$E_{HS,GHP}$	adsorption gas heat pump energy need for cold heat sink
E_{PV}	PV electricity production
$E_{PV/T}$	hybrid solar collectors electricity production
$E_{RES,GHP}$	actual renewable energy for adsorption gas heat pump cold heat sink
$E_{RES,HP}$	aerothermal energy for heat pump cold heat sink
ES_{H2}	hydrogen energy share in the energy scenario
ES_{PV}	PV electricity share in the energy scenario
f_{EH}	electric heater fraction
f_{RES}	renewable energy fraction
K_{PV}	correction factor to account for PV energy losses
$K_{PV/T}$	correction factor to account for PV/T energy losses
N_{days}	number of days
$\eta_{el,CHP}$	combined heat and power electrical efficiency
$\eta_{el,Grid}$	national Grid efficiency
$\eta_{h,CHP}$	combined heat and power heat recovery efficiency
$\eta_{h,PV/T}$	hybrid solar collectors heat recovery efficiency
PSH_{daily}	daily peak sun hours
$PTHR_{CHP}$	combined heat and power power-to-heat ratio
PV_{share}	solar energy technologies share

Abbreviation

AC	alternating current
AGHP	adsorption gas heat pump
CHP	combined heat and power
COP	coefficient of performance
DC	direct current
DNI	direct normal irradiation
EH	electric heater
EHP	electric heat pump
GHP	gas heat pump
GRG	generalized reduced gradient
H2	hydrogen
H2NG	hydrogen enriched natural gas
KPI	key performance indicator
NG	natural gas
nZEB	net zero energy building
P2G	power to gas
PEC	primary energy consumption
PTHR	power to heat ratio
PV	photovoltaics
PV/T	hybrid solar collector
RES	renewable energy sources
RS	receiving surface
URS	unit of receiving surface

considered. The suitability of those blends with well-proven technologies is already demonstrated [18,19].

This paper focuses on the role of hydrogen enriched natural gas (H2NG) in hybrid energy systems for energy refurbishment purposes, considering merchandised technologies such as photovoltaics (traditional and hybrid), combined heat and power plant (CHP) and heat pump (electric and gas driven). Moreover, a comparison between those systems was discussed in terms of primary energy saving and renewable energy fraction. To do so, the first step is to identify the viable hybrid systems solution and to evaluate their compatibility with hydrogen application.

2. Methodology

As reported in Fig. 1, the traditional separated generation layout was compared to three different plant layout options: the first one is composed of a PV array and a two-stage electric heat pump (EHP); the second one is composed of photovoltaic thermal hybrid solar collector and a adsorption gas heat pump fuelled with H2NG blends; in the end, the third one consists of a CHP fuelled with H2NG blends and a two-stage EHP. The systems energy balance was calculated over one year period implementing the net metering option for renewable electricity release and withdrawal.

The first two layouts, on the right side of Fig. 1, involve the energy production by solar technologies, both electrical and thermal. The PV and PV/T arrays are meant integrated in the building typology, mainly on its roof. While, the third layout, on the left side of Fig. 1, could be applied when no roof surface is available for installation due to technical and/or architectural constraints. In the second and third layouts, at the bottom of Fig. 1, renewable hydrogen (H_2) contributes to meet the energy demand. The assumption of this study is that H_2 comes from renewables excess electricity conversion by means of power-to-gas option under a National Energy Policy. Furthermore, two different heat pump technologies were considered: two-stage EHP and gas driven AGHP for matching the high water temperature level (65–80 °C) required by the existing end-users. When AGHP is used, the PV/T thermal output represents its cold temperature heat sink. In this case, an auxiliary electric heater was considered to back-up the required thermal energy in winter season or cloudy days when direct normal irradiation (DNI) is low.

Those options were evaluated for a typical building, characterized by certain materials connected to the year of construction, in three locations in Italy: Northern (reference city Trento), Middle (reference city Rome) and Southern (reference city Palermo) areas. Each location entails a diverse Renewable Energy availability in terms of solar radiation.

Given that existing buildings entail design limitations due to architectural and technical constraints, the authors defined two different key performance indicators (KPIs). Those ones are built to provide the unit of receiving surface per building unit of thermal energy need for both PV and PV/T technologies. By these values, it is possible to calculate the required surface of the chosen solar energy technology so as to assess the technical feasibility of each aforementioned layout. It is important to point out that electrical net metering plays a key role in the yearly energy balance for the implemented solar technologies. Yet, the solar thermal energy from PV/T requires further management strategy to be used effectively: during the summer, the heat excess could supply the centralized domestic hot water system or be dissipated in order to mitigate the PV cell efficiency derating owing to the high surface temperature. Alternatively, seasonal thermal energy storage devices could be adopted but, they show several drawbacks such as volumetric capacity as well as siting issues in constrained environments.

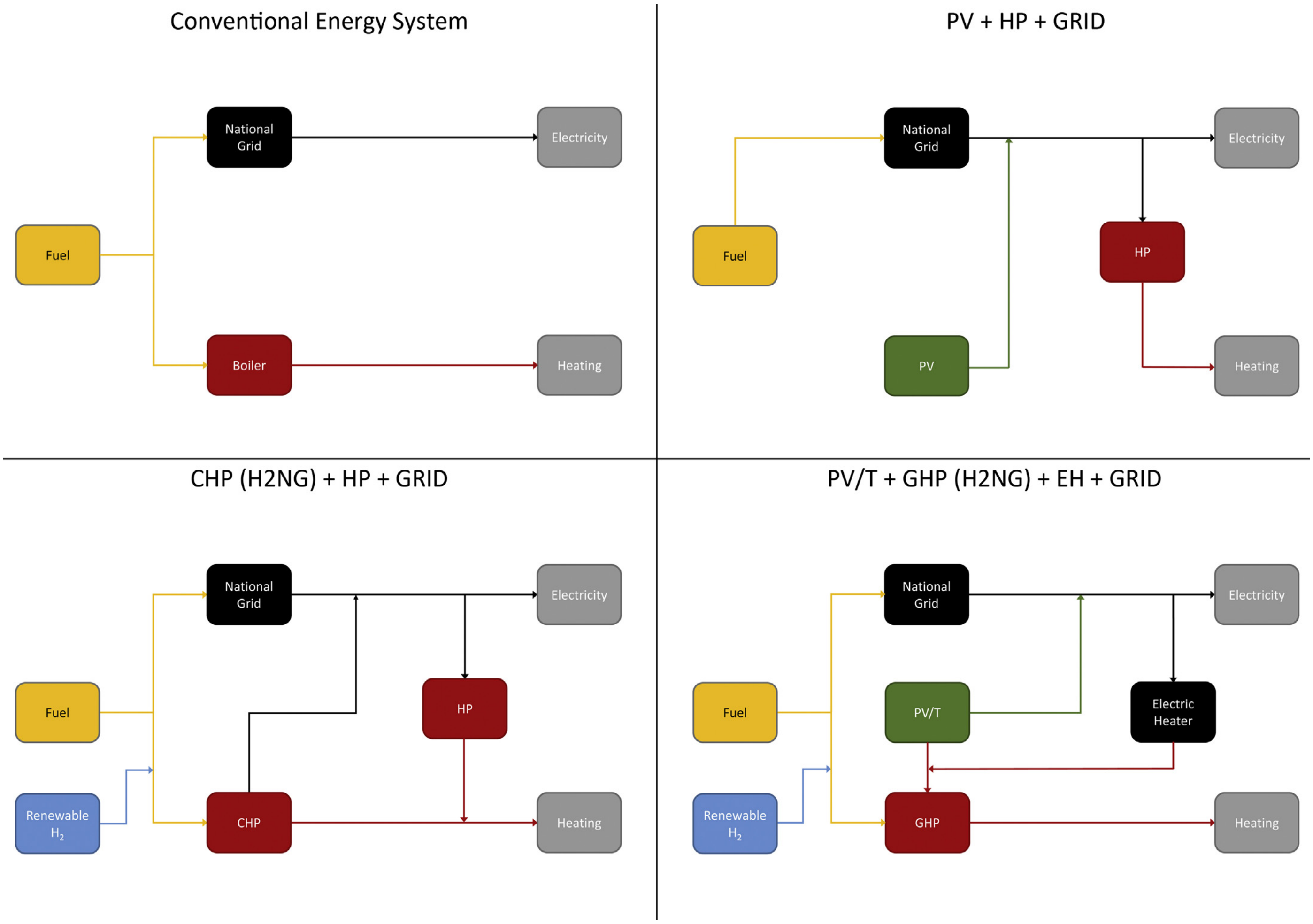

Fig. 1. The conventional energy system and the analyzed energy system layouts.

Eq. (1) allows to calculate the total PV receiving surface and its electricity production required to feed the electrical heat pump, as in layout PV + HP + GRID in Fig. 1.

$$\frac{URS}{E_{D,H}} = \frac{URS}{E_{el,PV}} \cdot \frac{E_{el,PV}}{E_{H,HP}} = \frac{URS}{E_{el,PV}} \cdot \frac{E_{el,PV}}{COP \cdot E_{el,HP}} \quad (1)$$

Similarly, Eq. (2) allows to calculate the total PV/T receiving surface and its thermal energy production to guarantee the correct operation of the Gas Heat Pump cold sink, as in layout PV/T + GHP + EH + GRID in Fig. 1.

$$\frac{URS}{E_{D,H}} = \frac{URS}{E_{HS,GHP}} \cdot \frac{E_{HS,GHP}}{E_{H,HP}} = \frac{URS}{E_{H,PV/T}} \cdot \left(1 - \frac{1}{COP_{GHP}}\right) \cdot (1 - f_{EH}) \quad (2)$$

Furthermore, it is noteworthy that Eq. (2) accounts for the contribution of the auxiliary thermal energy deriving from the electric heater by means of the term f_{EH}, i.e. electric heater fraction. Then, referring to the layout CHP + HP + GRID, no further KPIs were required.

In accordance with the subject of the study, the primary energy consumption was identified as the objective function for the optimization process in yearly normalized energy balance of all the scenarios. Additionally, the renewable energy fraction has been calculated as further indicator as requested by the updated version of Building Energy Performance Certification [20]. Moreover, a sensitivity analysis was carried out by varying the following energy drivers:

- End-user power-to-heat ratio (PTHR), which is defined as the ratio between the electrical energy consumption and the thermal one for the building and it ranges between 0.053 and 0.429 for all system layouts apart from PV/T + GHP + EH + GRID for values lower than 0.121 where it implies negative energy flows.
- PV electricity share, which is defined as the fraction of electricity demand covered by PV array production for the PV + HP + GRID scenario.
- Coefficient of performance (COP) of the adsorption gas heat pump, which ranges between 1.2 and 1.5 for the PV/T + GHP + EH + GRID scenario.
- Electrical heater fraction, which is defined as the fraction of thermal energy in the AGHP cold sink covered by the electric heater for the PV/T + GHP + EH + GRID scenario.
- Hydrogen energy share, which is defined as the fraction of fuel supply covered by renewable hydrogen from power-to-gas application for the PV/T + GHP + EH + GRID and CHP + HP + GRID scenarios.

Then, two maps were elaborated to calculate easily the aforementioned KPI so as to design the solar technology array starting from the building heating demand. Finally, the role of hydrogen by means of its addition to natural gas well-proven technologies, i.e. CHP and AGHP, was discussed in terms of overall system efficiency gain and hydrogen energy contribution to the total energy demand.

2.1. Energy models

In this section, the analytical models of each energy system layout have been presented. Referring to the PV + HP + GRID system, Eqs. (3) and (4) represent the electric energy and the thermal energy balance, respectively:

$$E_{D,el} = E_{Grid} + E_{el,PV} - E_{el,HP} \tag{3}$$

$$E_{D,H} = E_{H,HP} \tag{4}$$

In Eq. (5), the electrical energy demand of the EHP was defined:

$$E_{el,HP} = COP \cdot E_{H,HP} \tag{5}$$

Then, the PV electricity share in the energy scenario is identified in Eq. (6):

$$ES_{PV} = \frac{E_{el,PV}}{E_{D,el} + E_{el,HP}} \tag{6}$$

Finally, the primary energy consumption (PEC) was calculated as the energy from fuel burning divided the National Grid generation efficiency, as in Eq. (7):

$$E_{fuel,sys} = \frac{E_{Grid}}{\eta_{el,Grid}} \tag{7}$$

As regards the PV/T + GHP + GRID, the heating supply is entirely provided by the AGHP as shown in Eq. (8). Its PEC consumption is associated to its COP defined in Eq. (9).

$$E_{D,H} = E_{H,GHP} \tag{8}$$

$$E_{fuel,GHP} = \frac{E_{H,GHP}}{COP_{GHP}} \tag{9}$$

As reported in Eq. (10), the heat coming from PV/T and the electrical heater matches the heat demand of the AGHP cold sink.

$$E_{HS,GHP} = E_{H,PV/T} + E_{H,EH} \tag{10}$$

Similarly to the previous energy system, the electricity balance was shown in Eq. (11) as well as the technology PEC in Eq. (12).

$$E_{D,el} = E_{Grid} + E_{el,PV/T} - E_{el,EH} \tag{11}$$

$$E_{fuel,sys} = \frac{E_{Grid}}{\eta_{el,Grid}} + (E_{fuel,GHP} - E_{H2}) \tag{12}$$

The equation system is completed by the definition of hydrogen energy share and electrical heater fraction, as in Eqs. (13) and (14).

$$ES_{H2} = \frac{E_{H2}}{E_{fuel,GHP}} \tag{13}$$

$$f_{EH} = \frac{E_{el,EH}}{E_{HS,GHP}} \tag{14}$$

So, the model for CHP + HP + GRID entails the modification of electrical and thermal energy balances as well as the PEC consumption as in Eqs. (15)–(17). Then, the CHP energy supply is calculated in Eq. (18).

$$E_{D,el} = E_{Grid} + E_{el,CHP} - E_{el,HP} \tag{15}$$

$$E_{D,H} = E_{H,CHP} + E_{H,HP} \tag{16}$$

$$E_{fuel,sys} = \frac{E_{Grid}}{\eta_{el,Grid}} + (E_{fuel,CHP} - E_{H2}) \tag{17}$$

$$E_{fuel,CHP} = \frac{E_{el,CHP}}{\eta_{el,CHP}} \tag{18}$$

For the CHP fueling, the hydrogen energy share was defined by Eq. (19).

$$ES_{H2} = \frac{E_{H2}}{E_{fuel,CHP}} \tag{19}$$

Table 1
Calculation parameters for energy systems options.

PV + HP + GRID	PV/T + GHP + GRID	CHP + HP + GRID
	η_{GRID} = 0.42, $PTHR$ = 0.429	
COP_{EHP} = 2.5	COP_{GHP} = 1.45	COP_{EHP} = 2.5
$\eta_{el,PV}$ = 0.12	$\eta_{el,PV/T}$ = 0.14	$\eta_{el,CHP}$ = 0.33
PV_{share} = 0.65	$\eta_{h,PV/T}$ = 0.36	$\eta_{h,CHP}$ = 0.5
	$\eta_{el,EH}$ = 0.8 f_{EH} = 0.2	$PTHR_{CHP}$ = 0.66
	f_{H2} = 30 %vol., ES_{H2} = 0.115	f_{H2} = 30 %vol., ES_{H2} = 0.115

In Eq. (20), the CHP power-to-heat ratio can be express by the ratio between electricity and thermal energy outputs:

$$PTHR_{CHP} = \frac{E_{el,CHP}}{E_{H,CHP}} \tag{20}$$

In this scenario, the equation system solution depends on a further variable, the electricity provided by the CHP. To fix this parameter, the GRG non-linear optimization algorithm was used in order to minimize the PEC.

Finally, the layouts were compared by calculating the renewable energy fraction. That indicator accounts for the RES contribution in the overall electrical and thermal energy demand. In Eqs. (21)–(23) the parameter is defined for each layout.

$$f_{RES(PV+HP+GRID)} = \frac{E_{RES,HP} + E_{PV}}{E_{D,el} + E_{D,h}} \tag{21}$$

$$f_{RES(PV/T+GHP+GRID)} = \frac{E_{RES,GHP} + E_{el,PV/T} + E_{H2}}{E_{D,el} + E_{D,h}} \tag{22}$$

$$f_{RES(CHP+HP+GRID)} = \frac{E_{RES,HP} + E_{H2}}{E_{D,el} + E_{D,h}} \tag{23}$$

Here $E_{RES,HP}$ and $E_{RES,GHP}$ indicate the cold heat sink of the heat pumps, i.e. aerothermal for the first and the third layouts and the PV/T thermal output for the second one. E_{PV} and $E_{el,PV/T}$ are the electrical output from solar energy conversion. Then, E_{H2} is the hydrogen energy contribution coming from a foreseeable power-to-gas application to mitigate the renewables capacity firming at national scale.

3. Materials

In order to perform the simulations of all base scenarios, technical assumptions on devices efficiency, RES share and hydrogen energy share were made. Then, data from TABULA project [21] was selected to understand the common thermal and electric energy needs of real buildings and their different typologies. Moreover, renewable energy capability deriving from solar conversion was estimated by the use of the peak sun hour method. The advantage of peak sun hours is that they can be multiplied directly by rated power of a solar PV system obtaining the daily production. The calculation is based on 1000 W/m^2 of DNI with a correction factor, which accounts for soiling effects and energy losses caused by wires and DC/AC converter as well as heat losses related to the thermo-hydraulic loop for PV/T.

3.1. Calculation parameters

Table 1 outlines in a systemic overview the technical assumptions made for calculations of the normalized yearly energy balance related to layouts PV + HP + GRID, PV/T + GHP + GRID and CHP + HP + GRID. In detail, the common parameters are the Grid efficiency (η_{GRID}) and the end-user power-to-heat ratio.

As regards layout PV + HP + GRID, the PV electrical efficiency ($\eta_{el,PV}$), the EHP coefficient of performance and the PV share are reported. Layout PV/T + GHP + GRID has in addition to the same

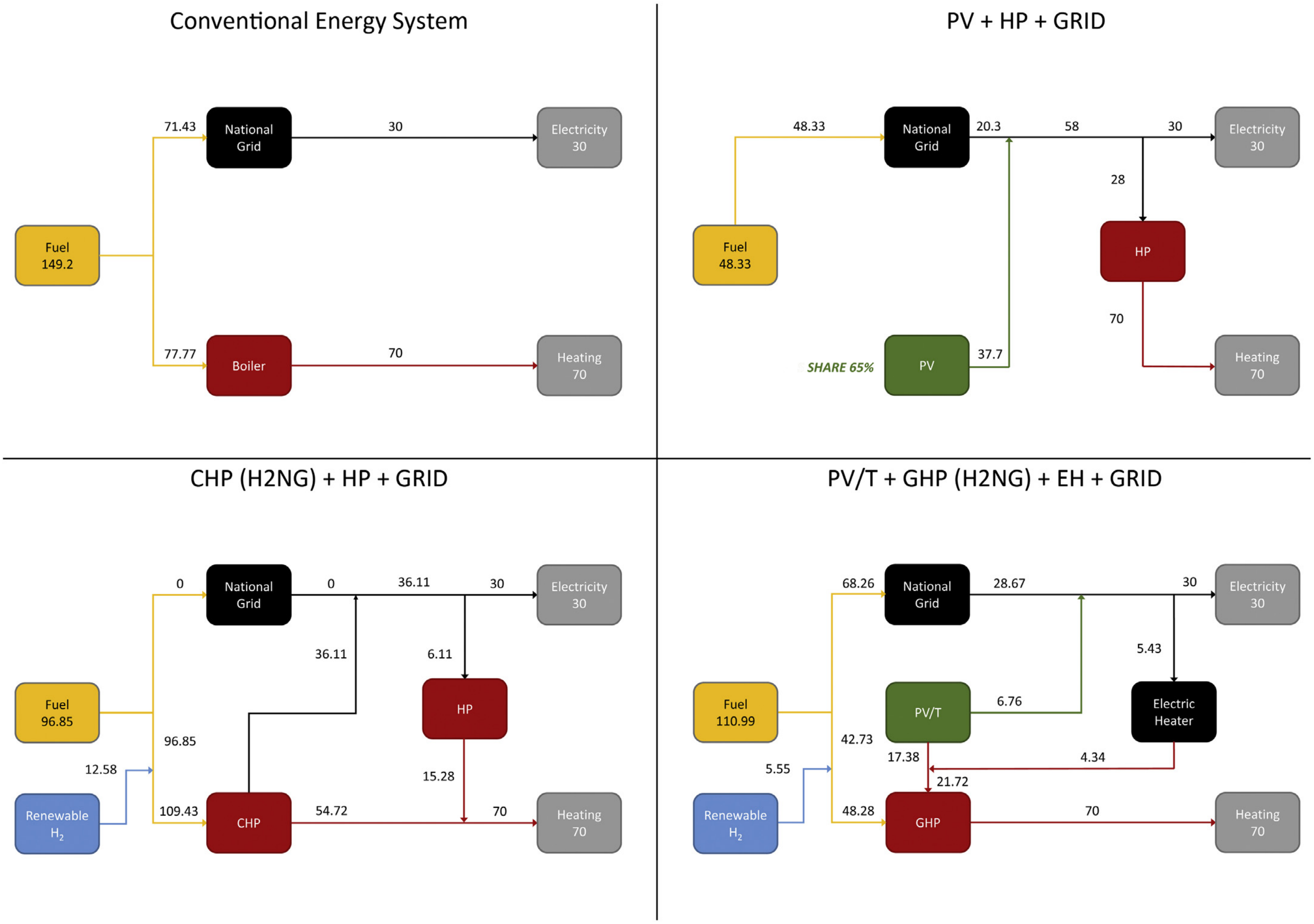

Fig. 2. The normalized energy balance of the conventional energy system and the analyzed energy system layouts.

information, the PV/T heat recovery efficiency ($\eta_{h,PV/T}$), the electric heater efficiency ($\eta_{el,EH}$) and its share on the AGHP cold heat sink (f_{EH}), the H_2 volumetric fraction in the H2NG blend (f_{H2}) and its energy share (ES_{H2}). Finally, referring to the layout CHP + HP + GRID, both CHP electrical ($\eta_{el,CHP}$) and heat recovery ($\eta_{h,CHP}$) efficiency values were reported as well as its Power-To-Heat Ratio ($PTHR_{CHP}$). Therefore, a comparison between those reference systems in meeting the same energy demand is made by the two aforementioned indicators: primary energy consumption ($E_{fuel,sys}$) and renewable energy fraction (f_{RES}).

In Fig. 2, the normalized energy balance of the reference scenario for conventional and hybrid systems are depicted. The energy flows on yearly base have been calculated to meet a normalized electricity demand equal to 30 and a normalized thermal energy one equal to 70, i.e. an end-user PTHR equal to 0.429.

By making the comparison to the conventional energy scenario, the PV + HP + GRID denotes the highest decrease in PEC (−67.7%) as well as the highest RES fraction equal to 79.7% of the energy supply. While, referring to the PV/T + GHP + GRID, it showed the lowest PEC change equal to −25.6% and a RES fraction equal to 34% of the energy supply. Thus, the CHP + HP + GRID scenario has the medium PEC change around −35% whereas the associated RES fraction is the lowest one equal to 27%. The observed anomaly is that in the last two scenarios the highest RES fraction does not correspond to lowest PEC. For this reason, a further investigation was required in order to understand the link between renewables penetration and overall system efficiency. Therefore, the authors carried out a sensitivity analysis with changes in systems boundary conditions: end-user energy demand ratio (PTHR), solar energy technologies share (PV_{share}) and backup electrical supply (f_{EH}).

3.2. The building energy consumption

The quality of the building energy demand becomes crucial in terms of heating and electricity contributions. So, its power to heat ratio (PTHR) can be assumed as the parameter to analyze the energy demand allocation. Based on the European Research Project TABULA [21], a set of buildings were considered and their PTHRs were calculated. As aforementioned, a PTHR equal to 0.429 is related to the most common standards in new dwellings. For instance, a typical new flat is provided by an electricity metre with 3–5 kW_{el} of rated power and an independent boiler/heat pump with 8/10 kW_{th}. Referring to existing buildings, those values entail a different PTHR. This is the reason why a sensitivity analysis based on PTHR is required to identify the most effective plant layout within the presented energy systems and the associated primary energy consumption (PEC). In order to verify the technical feasibility of layouts PV + HP + GRID and PV/T + GHP + GRID, a preliminary analysis of the available surface for both PV and PV/T arrays integration must be carried out. This step can be input in the design process for new buildings while, in case of existing building refurbishment, architectural constraints have to be accounted due to their key role for the aforementioned RES integration.

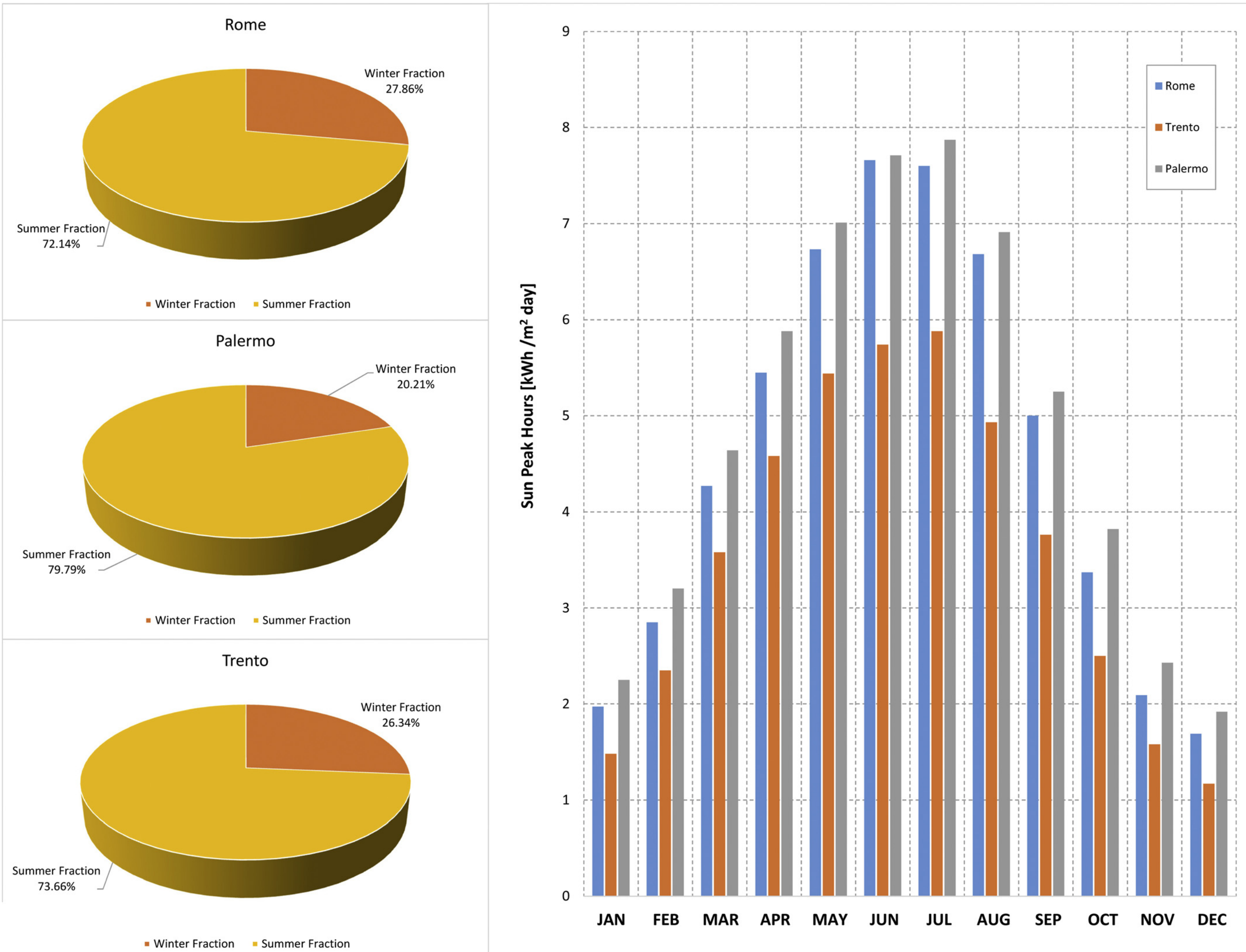

Fig. 3. Monthly peak sun hours and seasonal distribution in three Italian locations.

3.3. Discussion on solar energy availability for KPIs calculation

Referring to Fig. 2, it emerged that the solar heat pump (PV + HP + GRID) is the best solution but, two main typologies of constraints must be considered:

- limitations on roof surface availability for PV installations due to architectural constraints mentioned in Section 3.2;
- limitations associated to the mismatch between solar energy availability and its heat demand during the winter season.

To cope with those issues, in Fig. 3 the monthly peak sun hours were reported for three different locations in Italy as well as the seasonal percentage distribution of them. The winter period was calculated as defined by law in force [22] for each climatic zone. The available solar energy during the winter ranges between 20% and 28% of the total yearly one. Once the net metering option is implemented for electrical PV energy production, the solar energy availability distribution over the year becomes not crucial, since the high summer production balances the low winter one. Differently, the heat provided by the PV/T cannot be deferred, if a heat storage facility installation is excluded but, it has to be balanced by an electrical heater or backup boiler to guarantee the correct operation of AGHP.

Eqs. (24) and (25) provide the final energy output when the receiving surface (RS) is known and is well oriented. Furthermore, by those equations the soiling effects and the other energy losses are taken into account by the correction factors for PV and *PV/T*, i.e. K_{PV} and $K_{PV/T}$, respectively.

$$E_{el,PV} = PSH_{daily} \times N_{days} \times \eta_{el,PV} \times RS \times K_{PV} \tag{24}$$

$$E_{h,PV/T} = PSH_{daily} \times N_{days} \times \eta_{h,PV/T} \times RS \times K_{PV/T} \tag{25}$$

In the simulations performed by the authors, K_{PV} was assumed equal to 0.8 while, $K_{PV/T}$ equal to 0.7.

Finally, even though the PV and PV/T backup solutions were identified, i.e. GRID supply and auxiliary heat production, respectively, the PV sizing was done on yearly base while, the PV/T sizing was based on the energy availability in winter season.

4. Results and discussion

Since the aim of this study is to explore the opportunity to increase the renewables share in existing buildings, the authors found that the best solution, i.e. the solar heat pump (PV + HP + GRID), is not easily suitable for built-up areas due to several constraints. Therefore, strengths and weaknesses of hybrid systems involving solar energy were discussed once those solutions substitute the best one because not feasible. To account for the

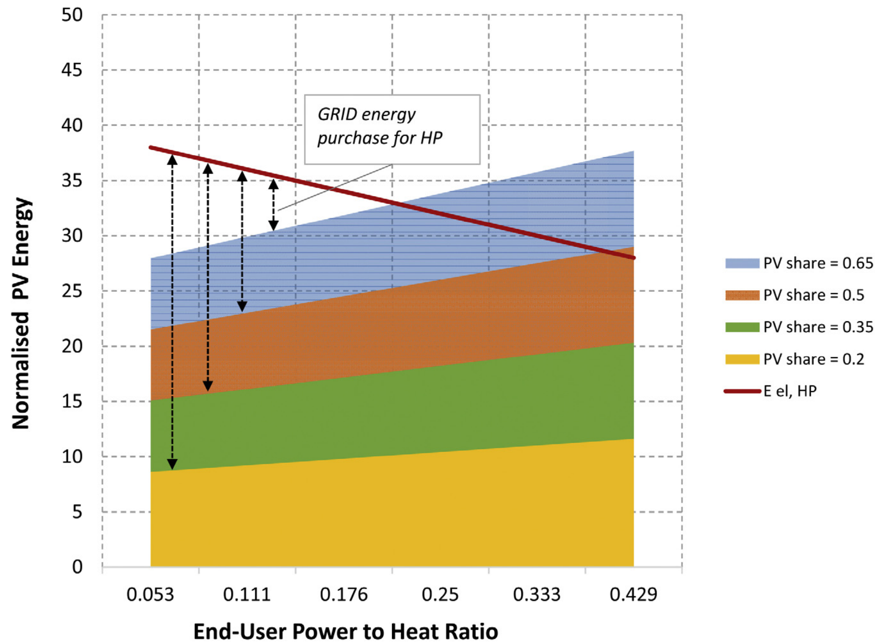

Fig. 4. Normalized PV energy with changes in PV share, heat pump electrical need and grid purchase vs. end-user PTHR.

mentioned limitations, the foreseeable alternative was to partially substitute the fuel typology supply in the thermodynamic cycles to make the existing building stock more renewable without changes in the energy system architecture. Fig. 4 depicts the normalized solar electricity production and the EHP electricity demand with changes in end-user power-to-heat ratio and PV share.

From data it emerged that the whole PV supply of the EHP occurs at 50% of PV share and high PTHR values. Additionally, a further increase in PV share allows to identify a threshold in PTHR equal to 0.2, approximately.

This result entails a large roof surface to install PV array, specific bioclimatic building design and higher electricity demand compared to the heating one. Actually, the first condition does not occur due to architectural constraints; the second one misses in the dwellings built after the Second World War which represent the great part of the building stock; and, the third one is not present due to low energy performance of building envelopes. Currently, electrification is considered a viable option to increase the building PTHR. To do so, the introduction of electricity-driven heating systems is promoted but this kind of strategy belongs only to nearly zero energy buildings (nZEB) deployment along with the reduced heating demand by their enhanced building envelope performance. Furthermore, even if the roof surface is available such as terraced roof, the EHP demand is not totally covered by PV due to the high heating one.

Having said, the map in Fig. 5 allows to calculate the unit of receiving surface (URS) per unit of heating demand for solar electrical heat pump case, by using the following procedure:

- starting from the building PTHR, it is possible to intercept the design PV share curve;
- having identified that point, it is possible to move horizontally to choose the location. Finally, the x-projection is the KPI value defined in Eq. (1).

This value has to be multiplied by the total heating demand to obtain the total RS (receiving surface). So, by comparing this value with the actual available roof surface of the building typology, the solar EHP feasibility could be evaluated.

A similar approach was adopted to calculate the second KPI related to the PV/T unit of receiving surface.

The logical pathway is more complex due to the absence of thermal energy net metering where no storage is present, the variation of AGHP performance coefficient, the backup auxiliary share and the locations. The PV/T energy output will be the AGHP cold heat sink.

Thus, the map in Fig. 6 can be used by the following procedure:

- starting from the building PTHR, it is possible to intercept the AGHP COP curves;
- having identified that point, the designer will go for the Electrical Heater fraction;
- hence the normalized thermal energy to feed the cold heat sink by PV/T supply can be evaluated.
- Finally, choosing the location by the interception of the curve, the y-projection is the KPI value defined in Eq. (2) for a given f_{EH} value.

The electricity coming from the PV/T is used in the system with or without the net metering option. The AGHP supply remains the fossil fuel. This latter could be made partially renewable by the integration of power-to-gas such as hydrogen enriched natural gas blends application. In this way, the use of this ecofuel supply avoids changes in the well-proven energy systems as well as its temperature levels and, consequently, terminals size. It is particularly suitable for those buildings where the HVAC devices are part of the listed interior design such as historical villas used as museum [23,24]. In Fig. 7, the layouts PV + HP + GRID, PV/T + GHP + EH + GRID and CHP + HP + GRID presented in Section 2 were compared in terms of normalized primary energy consumption (PEC). A further analysis shows the sensitivity to the PV share for layout PV + HP + GRID and to the Hydrogen volumetric fraction for other ones. In this figure, the normalized PEC is function of the end-user PTHR. Basically, as the PTHR increases the normalized PEC does the same. In detail, for a PV share higher than 50%, the PV + HP + GRID is the best solution. Yet, for PTHR equal to 0.12 layout PV/T + GHP + EH + GRID with H2NG@30% shows the lowest PEC (Fig. 8).

Generally, this latter layout results the most sensitive to PTHR owing to the highest slope. It is important to point out that for PTHR

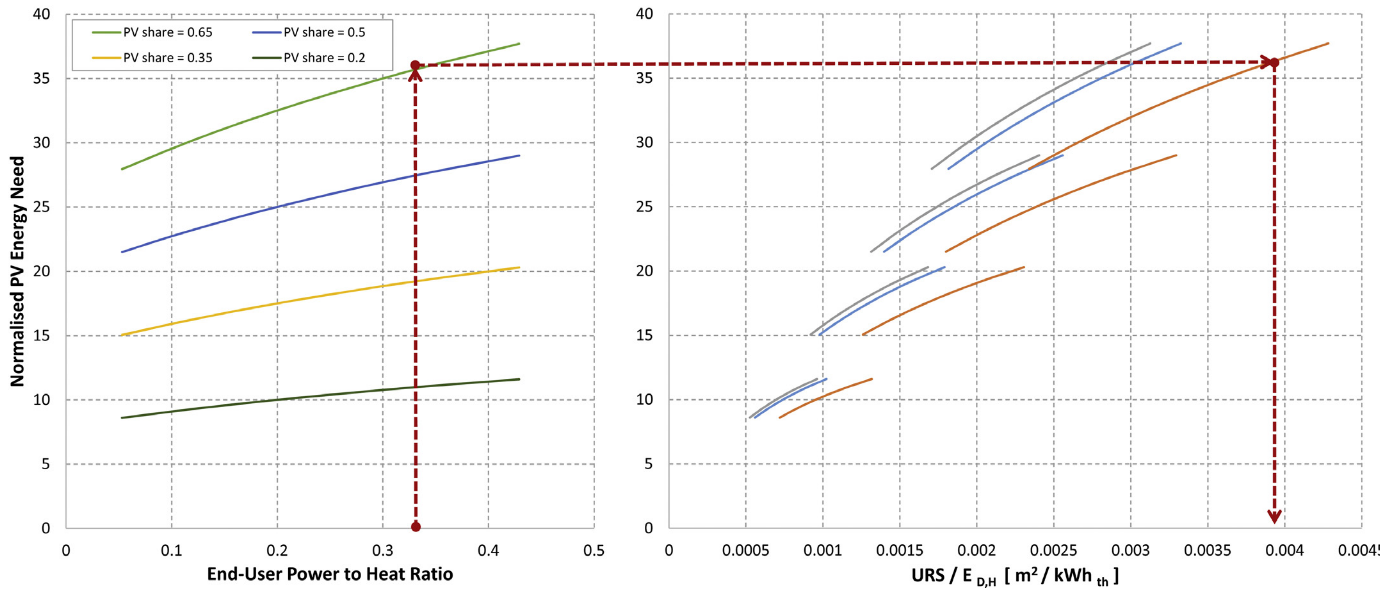

Fig. 5. Combined map to assess the unit of receiving surface (URS) per unit of heating demand for electric heat pump driving, with changes in geographical areas.

lower than 0.3, an AGHP fuelled with H2NG is the best solution if compared to low PV share in layout PV + HP + GRID, i.e. 20% and 35%. That is the case of limited PV array extension due to the lack of available roof surface. Referring to CHP + HP + GRID, the optimized solution led to a CHP electrical power size able to feed the HP and provide the all electrical needs of the building as well, to avoid the electricity purchase from the National Grid. The end-user behaviour is similar to an off-grid system.

Since the second analysis focused on the renewable fraction of energy supply, in Fig. 7 all the f_{RES} calculation results were depicted with changes in PTHR. For all energy scenarios, the lower PTHR implies the higher RES fraction. In detail, the configuration PV + HP + GRID shows the highest RES integration. While, the GHP + HP if compared to the mentioned layout at 20% and 35% of RES share, it has low RES integration but still showing high performance in primary energy reduction. So, depending on the boundary conditions related to the energy system, the objective function could be the PEC or the RES integration. It is noteworthy that the highest RES integration does not ensure the lowest PEC due to different ratio between the availability of surface for solar energy production and its role in the energy system layout. So, solar energy stored by means of electrolysers at National or District scale could be more effective to meet both electricity and heating demand than the direct produced one, even if there is low conversion efficiency. This conclusion is based on the evidence of architectural integration in existing buildings is hardly limited for PV solutions. Indeed, hydrogen can be burnt with NG so that to supply heat at higher efficiency, resulting more suitable for dwellings characterized by low PTHR values.

Referring to the PV/T + GHP + GRID configuration, it is noted that this is the only one which involves a direct RES contribution from solar energy and an indirect one owing to the use of an Eco-Fuel, i.e. H2NG. This latter is composed by a renewable fraction, the Hydrogen deriving from the National RES electricity excess conversion stored in NG pipelines. Finally, where no roof surfaces are available for PV or PV/T installation, the CHP + HP fuelled with H2NG is the solution [25].

4.1. The role of Hydrogen

Since the aim of the study is to evaluate the potential role of hydrogen application in existing conversion systems for building refurbishment, the following section was built. In detail, referring to PV/T + GHP + GRID and CHP + HP + GRID which require the NG supply, the overall system efficiency gains with changes in PTHR were analyzed when different Hydrogen fractions were added to methane. As aforementioned the PV + HP + GRID is the most effective solution but its viability depends strongly on available roof surfaces, often limited for architectural constraints. Hence, the well-proven energy systems or the already installed ones could be upgrade in terms of renewability by ecofuels feeding. The Hydrogen effects were considered in the second and third layouts since recent research lines demonstrated its effectiveness in listed buildings [26].

Fig. 9, on the left side, shows the CHP-based conversion efficiency where its Normalized electricity production is superimposed. Similarly, on the right side of the same Figure, the AGHP-based conversion efficiency is shown along with its Normalized Heating production. From data, it emerged that as the CHP Normalized electricity increases due to the higher PTHR values, the overall efficiency goes down. Differently, for AGHP overall efficiency decreases as well as Normalized Heating production. In both Fig. 9 sides, by adding more Hydrogen, the overall efficiency rises. Yet, it is important to point out that for CHP case the overall energy efficiency gain is almost constant for all PTHR values. While, for AGHP case, this value is sensitive to the PTHR value, being higher at the lowest PTHR values. For instance, when H2NG @30 %vol. is applied at PTHR equal to 0.121, that gain is about 0.17 and 0.68 for CHP and AGHP cases, respectively. At the highest PTHR value, i.e. 0.429, those gains correspond to 0.18 for both CHP and AGHP cases.

Fig. 10 depicts the Hydrogen energy contribution to the total energy needs in the CHP + HP + GRID and PV/T + GHP + GRID in the left and right side, respectively. The highest Hydrogen energy contribution is obtained with the highest Hydrogen volumetric fraction in the blend. In the CHP case, it occurs at high PTHR values while, in the AGHP case the highest value correspond to the lowest PTHR one. Those different trends are due to the diverse outputs of the machines: both electricity and heat from the CHP which is optimized to cover all the electricity demand as well as its increasing for high PTHR, whereas only heat from the AGHP which will decrease its contribution at PTHR increase. Given that a gain is obtained from H2NG application, when an existing building is even a listed one and no modifications can be done to its energy systems and associated terminals, the change in the supply entails a benefit in terms of

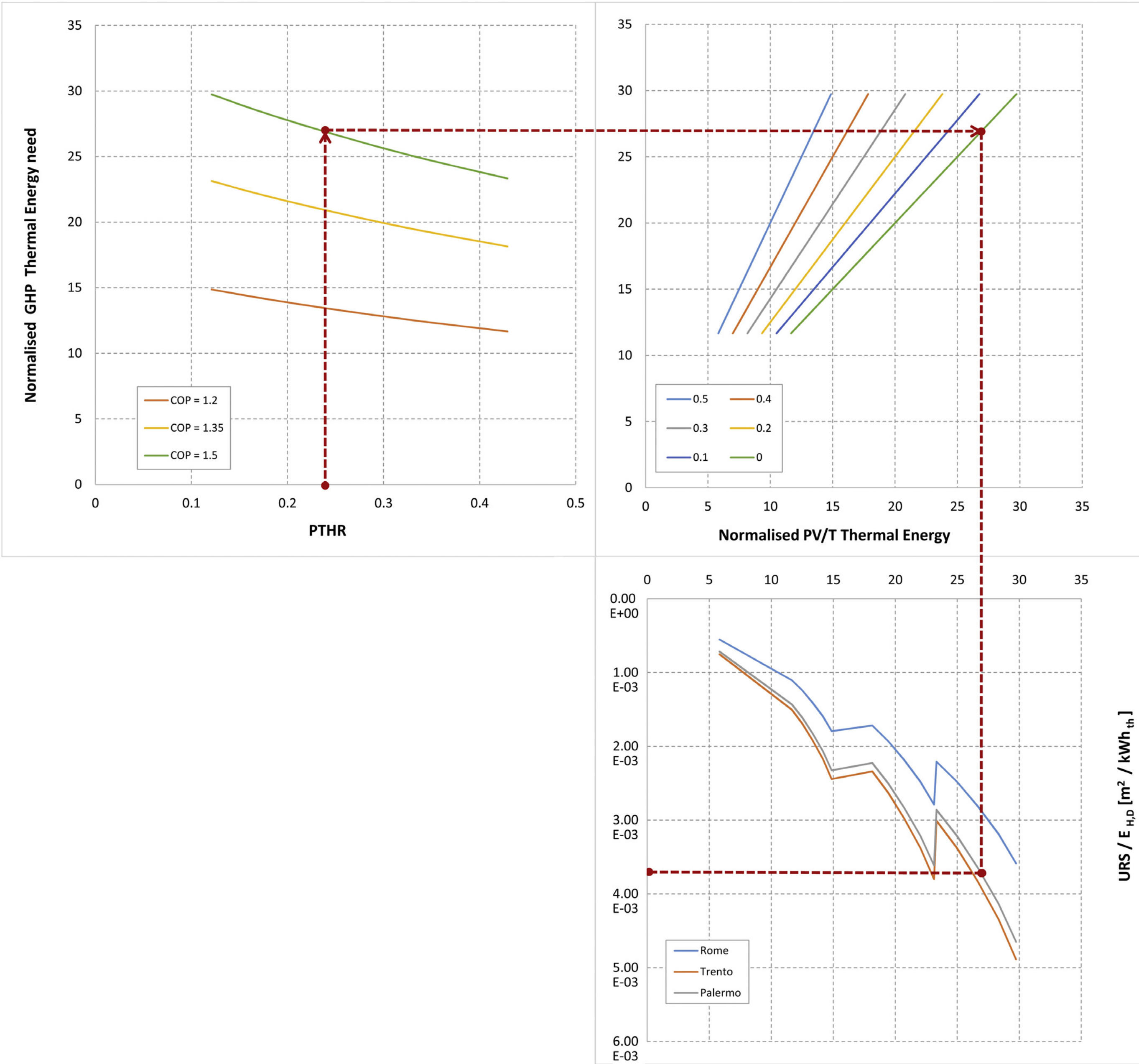

Fig. 6. Combined map to assess unit of receiving surface (URS) per unit of heating demand with changes in COP_{GHP}, electrical heater energy fraction and geographical areas.

renewability and efficiency. Thus, without changing the temperature levels, the machines and the terminals typology, often already part of the interior design, a H_2-based energy retrofitting solution is feasible. Furthermore, the Power-To-Gas solution at National or District scale avoid the installation of Hydrogen storage facilities by the use of Natural Gas pipelines.

The key point is that using Renewable Hydrogen enrichment in Natural Gas pipelines avoids the local installation of further renewable power plants along with their infrastructural issues [27]. In this way, the National dispatching and balancing strategies are not affected by this system layout but, the PEC objective can be still pursued. Additionally, the energy retrofitting design can start from the available Hydrogen fraction in the NG pipelines to identify a thermal management strategy by the AGHP use or an electricity/heating synergy by the CHP feeding. It is noteworthy that the AGHP solution allows to retrofit a larger number of buildings compared to the CHP one since AGHP requires a lower Hydrogen fraction.

4.2. Reference case studies

From data analysis of TABULA project, the energy consumption of a typical Italian dwelling ranges between 115 kWh_{th}/m^2y and 58 kWh_{th}/m^2y depending on the year of construction, where the first value is related to 1921 while, the second one to 2005. The analyzed typology is a multi-family house. Indeed, considering a single-family house the aforementioned values are even larger than the previous ones, i.e. 139 kWh_{th}/m^2y and 66 kWh_{th}/m^2y, respectively. The reference electricity consumption for both building typologies is 2500 kWh/y, independent of the construction year.

Considering a 100 m^2 flat, the heating demand ranges between 11,500 and 5800 kWh_{th}/y. The associated PTHRs are 0.21 and 0.43, respectively. New constructions, built after 2010, entail PTHRs

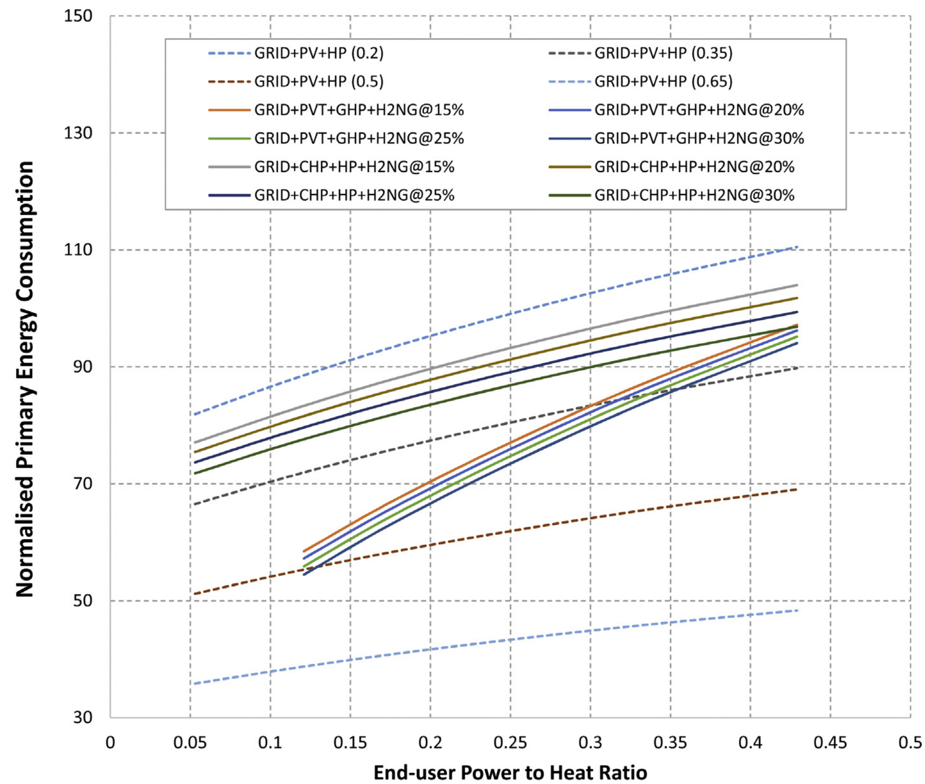

Fig. 7. Normalized primary energy consumption vs. end-user PTHR with changes in plant layout.

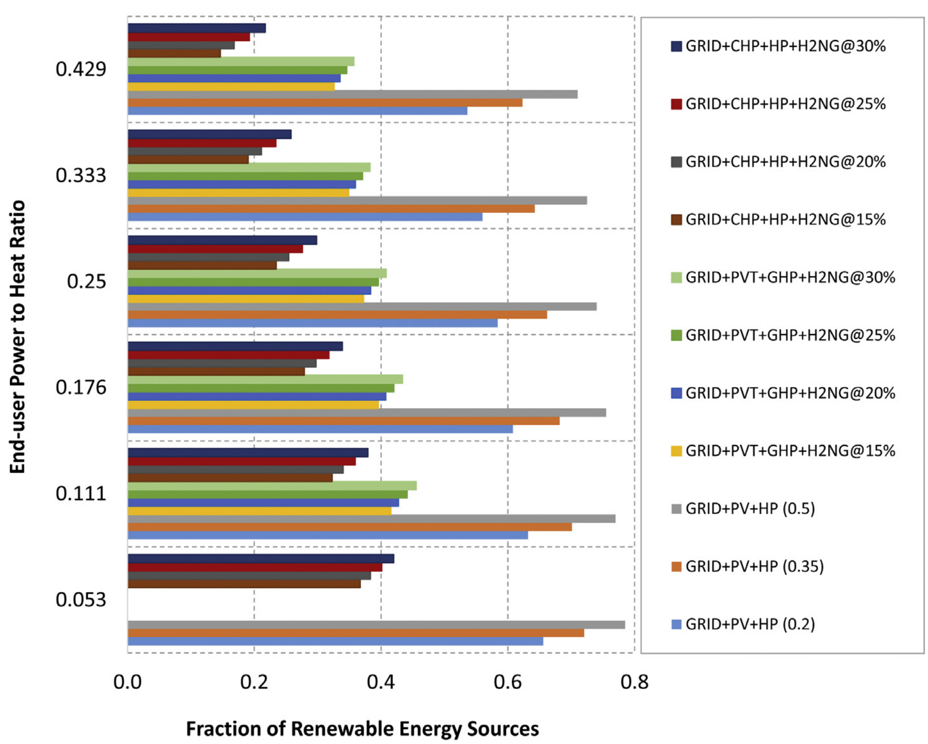

Fig. 8. End-user PTHR vs. RES fraction with changes in plant layout.

much higher than the previous ones. For instance, an NZEB shows a heating consumption per square metre equal to 20 kWh_{th}/y [28].

Having said, in Tables 2 and 3 the required receiving surface for both PV and PV/T related to PV + HP + GRID and PV/T + GHP + GRID scenarios were calculated by charts in Figs. 4 and 5 in the worst DNI conditions, i.e. for Northern Italy, and for the minimum and maximum PTHR values. From data it emerges that high PV share implies largest number of PV modules for each flat. This condition is usually feasible only in new buildings, designed properly for RES exploitation. Moreover, the required receiving surface results less

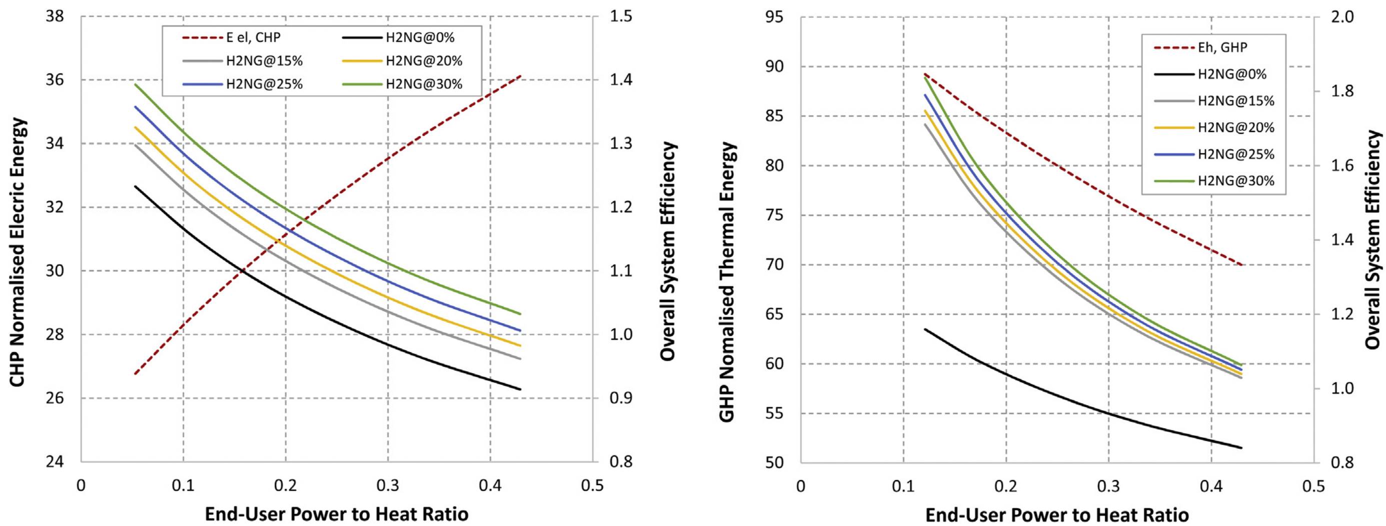

Fig. 9. Normalized primary energy consumption and overall system efficiency vs. end-user PTHR with changes in hydrogen fraction.

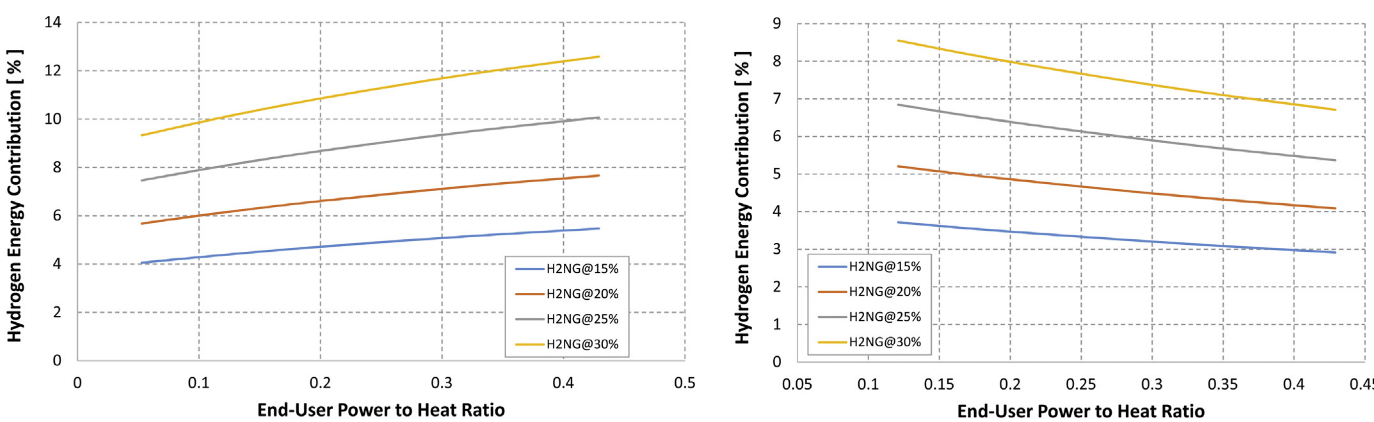

Fig. 10. Hydrogen energy contribution vs. end-user PTHR with changes in H2NG blends.

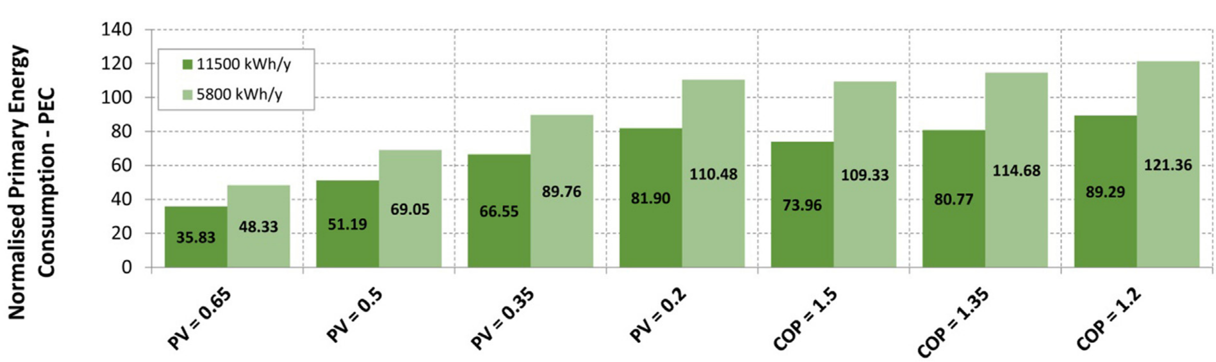

Fig. 11. Normalised PEC for PV + HP + GRID and PV/T + GHP + GRID fuelled with H2NG@30% vol. with changes in PVshare and COP_{GHP}.

sensitive to PTHR variations than to PV share. Indeed, the PV modules surface decreases slightly as the PTHR enhances. This is due to the fact that a lower heating demand entails a lower electricity need for the EHP driving, resulting in a larger electricity availability for the whole energy system. Nevertheless, the normalized PEC tends to be higher for PTHR maximum owing to the larger contribution of the Grid associated to the net metering option as in Fig. 11.

On the contrary, the required PV/T surface are much more sensitive to the PTHR variations. Within the considered range for sensitivity analysis, the hybrid modules surface is reduced more than 50%. That implies the possibility to find out thresholds in PTHR values beyond which the PV/T – based solution results more feasible than the solar heat pump, in terms of minor installation surface. Additionally, it is remarkable that the higher the COP_{GHP}, the larger the receiving surfaces are. Compared to the layout PV + HP + GRID equipped with PV, PV/T – based system results more suitable for RES integration in refurbishment of existing buildings depending on actual operating COP_{GHP} as well as the PTHR value. Yet, the normalized PEC is higher but in this way the hydrogen feeding the AGHP can contribute to increase the dwellings renewable fraction. Obviously, when shading issues or non-optimal orientation of the receiving surfaces occur as well as architectural constraints such as

Table 2
PV surfaces calculation for flat in reference buildings.

PV share	Required receiving surface (m^2)	
	Heating demand = 11,500 kWh/y (PTHR = 0.053)	Heating demand = 5800 kWh/y (PTHR = 0.429)
0.65	26.91	24.82
0.5	20.58	19.08
0.35	14.49	13.34
0.2	8.28	7.54

Table 3
PV/T surfaces calculation for flat in reference buildings.

COP_{GHP}	f_{EH}	Required receiving surface (m^2)	
		Heating = 11,500 kWh/y (PTHR = 0.121)	Heating = 5800 kWh/y (PTHR = 0.429)
1.5	0.2	33.35	14.21
1.35	0.2	28.13	12.23
1.2	0.2	18.4	8.7

in historical buildings, the Layout CHP + HP + GRID could be a viable technical solution to increase the energy production efficiency.

5. Conclusions

The study explored the performance of three energy systems in building energy refurbishment involving the Hydrogen use. Furthermore, a sensitivity analysis, based on building energy characteristics, machines efficiency and geographical areas variations was performed to assess strengths and weaknesses of current technologies able to burn hydrogen blended to natural gas. The main findings can be outlined as follows:

- Solar heat pump represents the best energy solution for heating plant and it has been chosen as the reference technology for the comparative analysis. Notwithstanding, high roof surface are required to strongly reduce the building primary energy consumption. It is feasible especially for new buildings and for the forthcoming nZEB.
- The energy scenario based on PV/T + GHP + GRID fuelled with hydrogen mixtures seems to be competitive with solar heat pump for existing building characterized by a PTHR value higher than 0.2 depending on actual operating COP_{GHP} of the gas heat pump as well as the auxiliary heater fraction.
- The CHP + HP + GRID scenario involving hydrogen mixtures results the worst in terms of primary energy consumption compared to the other solutions but it is foreseeable when solar energy technologies cannot be exploited owing to the lack of available surface or to architectural and landscape constraints.
- The use of hydrogen within CHP and AGHP leads to higher hybrid system efficiency values. The largest energy gain was registered when the hydrogen mixture at 30 %vol. was used with the AGHP for the lowest building power to heat ratio. Compared with the CHP performance the AGHP results strongly sensitive to PTHR, showing wide variations in energy gains, whilst those remain approximately constant for CHP case.

H2NG blends result the balanced effective solution for contemporary reducing the PEC and increasing RES fraction without installing new power capacity together with the associated issues. In such a way, H2NG improves the Grid balancing and promotes the NG Grid greening. Anyway, given that this paper wanted to analyze the systems feasibility only from the energy point of view, further investigations are required in order to take into account the capital expenditure, the discounted pay back and economic constraints as well to get higher level of carbon avoidance.

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