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Waste-heat utilization potential in a hydrogen-based energy system - An exploratory focus on Italy

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ABSTRACT

The target of the full decarbonisation by 2050 requires high penetration of renewables, with the development of overgeneration situations in the energy system. Hydrogen and electro-fuels could play a key role in hard-to-abate sectors and in grid balancing. By means of the developed NEMeSI model we study the Italian future energy mix, including several Power-to-X (P2X) options to accommodate high RES introduction. The model is set to solve a linear optimization problem, by optimizing the use of resources through the minimization of the supply costs. The use of excess power from renewables is evaluated in solutions such as hydrogen production and electro-fuels synthesis, coupled to Power-to-Heat and storage systems. The model studies the Italian case in a decarbonised scenario and provides an estimation of potential waste-heat recovery from the P2X processes, differentiating from low to high temperature waste-heat. Waste-heat can be used for district heating purposes or for power generation via organic Rankine cycle. Both high and low temperature heat recovery show a potential in the order of tens of TWh, with a preference for power generation use.

Keywords

Waste-heat recovery;
Power-to-X;
Power-to-Hydrogen;
oemof;
District heating
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1. *Introduction*

During the last decades, a growing interest has spread about the need to revolutionize the energy system, following a net-zero emission target.

Within the European Union, National Energy and Climate Plans (NECPs) [1] have been adopted by Member States to set the mid-term goals (2030) in a long-term pathway towards decarbonisation. Italy has committed to achieve a reduction of at least 40% of GHG emissions by that year, coupled with an increased share of Renewable Energy Sources (RES) (55% in power sector, 33.9% in the heating sector and at least 22% in the transport sector) [2].

This implies a potentially high level of unbalances in the power grid, that can be managed through storage and demand-side management. From a longer-term perspective, in 2050 a full decarbonization would be required, imposing a much higher RES presence in the energy system.

The need not to waste excess energy produced in peak periods requires decoupling of production periods and demand profiles. Pumped-hydro and battery storage will likely not be enough. Alternatives like hydrogen and synthetic fuels will play a key role, also because will enable the decarbonization in sectors not suitable for electrification. These processes also produce waste-heat as by-product which could be recovered for district heating purposes or for power production.

While waste-heat potential from industrial sector is widely investigated (e.g. [3–5]), increasing attention is being paid to the study of waste-heat recovery from P2X processes. Analyzing the behavior of waste-heat production from such processes in a decarbonized energy

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Abbreviations

DH:	District Heating
DHW:	Domestic Hot Water
DME:	Dimethyl Ether
EV:	Electric Vehicles
FT:	Fischer-Tropsch process
GHG:	Green-House Gases
HT:	High Temperature
LT:	Low Temperature
NECP:	National Energy and Climate Plan
NG:	Natural Gas
ORC:	Organic Rankine Cycle
P2G:	Power-to-Gas
P2H:	Power-to-Heat
P2L:	Power-to-Liquid
P2X:	Power-to-X
PEM:	Polymer Electrolyte Membrane
RES:	Renewable Energy Sources

system and estimating the recovery potential can be relevant for planning decarbonization pathways.

1.1. P2X and waste-heat

In this paper, P2X (Power-to-X) means the use and transformation of electricity into other energy carriers, namely: *Power-to-Heat* (P2H), the production of heat from electricity, *Power-to-Gas* (P2G), with the synthesis of hydrogen or methane, *Power-to-Liquid* (P2L), the production of electro-fuels, and lastly *Power-to-X-to-Power,* the production of an energy carrier and its reconversion back to electricity. Besides P2H, the interest for these possible sector coupling options is relatively recent.

A review for P2X processes is here presented, also providing a picture of related waste-heat. Starting from P2G, water electrolysis (i.e. the production of hydrogen and oxygen through electricity) is a well-known reaction, especially with alkaline electrolyzer cells, considered the most mature and commercialized solution [6,8–10], although many other technologies have been recently investigated. Summarized global reports provided by IEA [9], DEA [10], Snam [11], Shell [6] help to frame the state of art of ideas around hydrogen in the energy sector.

Increasing attention concerns the Proton Exchange Membrane, or Polymer Electrolyte Membrane (PEM) electrolysis. It provides higher flexibility and better coupling with dynamic power system and produces highly compressed hydrogen. Other solutions are still at R&D level. In particular, the high temperature Solid Oxide solution (SOEC) is suitable for coupling with systems that produce waste-heat [6,7].

In Power-to-Gas sector another possible solution concerns the methane synthesis, which could get cost savings coming from the already existing infrastructure (e.g. transmission line, storage tanks). Synthetic methane can be produced from a chemical reaction which involves carbon mono/dioxide and hydrogen. Two processes exist: the catalytic thermochemical methanation and the biological one. The former is currently the main application, operating at a temperature range of 200-550 °C. Catalytic methanation is a highly exothermic process, being suitable for some waste-heat recovery [7,12–14]. Biological methanation uses methanogenic microorganisms in the process, with a lower operating temperature (20-70°C) [6,14–16].

Power-to-Liquid can be relevant in hard-to-abate sectors (e.g. transport), where GHG emission reduction through electrification might be hard to achieve. Green hydrogen obtained from renewable power can be further transformed into so called *electro-fuels.* Through the combination with carbon, it is possible to obtain fuels such as jet-fuel, methanol, Dimethyl Ether (DME) and ammonia.

Several processes are currently under investigation, presenting potential for waste-heat recovery. It is the case of the Fischer-Tropsch (FT) process, a consolidated exothermic process in coal and gas sector to obtain fuels such as jet-fuel for aviation. FT could use renewable hydrogen and captured carbon molecule as feedstocks [17–19].

Methanol, whose synthesis is a highly exothermic process, would be useful for the maritime sector or as intermediate product for more complex fuels "(e.g. DME or jet-fuel) [20–24]. Dimethyl Ether shows peculiar characteristics which make it a suitable solution in internal combustion engines for transportation. It has properties similar to conventional fossil gasoline, although it is produced from biogas or methanol through a two-steps (or direct) reaction [17], with commercial application already present in California [25–28].

aviation fuel can be obtained also from methanol [13,15]. In parallel to the Power-to-Liquid pathway, similar synthetic fuels can be obtained from biomass feedstock: this option is named Biomass-to-Liquid, which presents some peculiarities in the intermediate transformation steps, with the main difference to use a bio-based feedstock [10].

Another energy carrier derived from hydrogen can be ammonia, which can be stored and transported in an easier way compared to pure hydrogen. It is obtained via industrial Haber-Bosch process and its applications cover naval transportation [21] or power generation via Fuel Cells (FC) [29–32].

There is also the possibility to use the synthetic products obtained from P2G and P2L to generate electricity back (Power-to-X-to-Power). As for the electrolyzers, several technologies currently exist, from the most consolidated Alkaline technology (AFC), the low temperature Polymer Electrolyte Membrane Fuel Cell (PEMFC), to the high temperature class represented by Molten Carbonate (MCFC) or the Solid Oxide ones (SOFC) [3,6]. They typically use pure hydrogen as reactant, but applications on the use of different energy carriers (e.g. ammonia) are conducted [30].

1.2. Aim of the paper and outline

From such a context, it emerges that in a hydrogen based decarbonized energy system the potential sources of waste-heat could be relevant. The aim of this paper is to explore the potential use of such heat in different applications, from the power generation via Organic Rankine Cycle (ORC) to a direct use for District Heating (DH) purposes. A decarbonized scenario for the Italian energy system is built and analysed through an energy system model developed by the authors.

In the remainder of the paper, the structure of the tool used for the analysis is presented (Section 2), followed by the input data and the analyzed case study (Section 3). In Section 4 the main results of the simulation are reported, while main outcomes and further developments are summarized in the conclusion (Section 5).

2. Method

In order to analyze the role of waste-heat from P2X in a future decarbonized Italian economy, a model of the Italian energy system was developed, based on the open-source *oemof* modelling framework [33] and its behavior was then analyzed in a exogenously defined scenario. In this Section the structure of the developed model, called NEMeSI, (National Energy Model for a Sustainable Italy) is presented.

NEMeSI is a publicly available model developed by the authors (code and input dataset of the version used in this paper can be found at [34])[1], based on the oemof framework, an open-source flexible model generator, written in Python [33].

The model is based on a linear programming problem. The objective function represents the overall supply cost for primary fuels. This includes costs for fossil fuels (e.g. natural gas) and for bio-based ones. In Table 1 the commodity costs included in the model are presented.

Table 1: Cost for primary fuels considered by the model for the decarbonized scenario (2050 horizon).

Primary fuel	2050 Commodity cost [€/MWh]*	Ref.
Natural gas	41.10	[35]**
Oil***	68.53	[35]**
Biomass	90.00	[36]
Biogas	16.00	[36]

* Costs include all the steps of the supply-chain of the commodity (eg. extraction, import, production, purchase)
** Some elaborations were made by the authors to keep track on the trend observed in the last years
*** The cost of oil is reported although the resource is not considered in the case study

By minimizing the use of primary resources, it is possible, as indirect effect, to minimize the production of carbon dioxide obtained in combustion processes too. The minimization of this emissions allows to study the energy system in a decarbonized configuration, by limiting the need of Carbon Capture and Sequestration technology (CCS) coupled with conventional power generation systems.

Oemof framework allows to solve the optimization problem considering both capital and operating costs: by considering the former, it returns the optimized installed capacity of the studied technology. However, the model generator does not allow to consider the entire period of transition (e.g. 2020-2050) before the simulated year.

Investment costs for new technologies (e.g. P2X ones) are particularly difficult to be estimated: geopolitical factors and economies of scale might determine considerable under or overestimations. Furthermore, the rationale of the presented study is to analyze the potential of waste-heat recovery from P2X processes in a decarbonised scenario, where conventional fossil sources should be minimized.

For these reasons, no capital expenditures were considered in the model and only commodity costs were considered for operating expenditures.

[1] Two version of NEMeSI exist: one for 2030 [42] and one for 2050. The paper refers to the 2050 configuration.

The objective function is expressed as follow:

$$obi\ function = \min\left\{\sum_t \sum_i \left[C_{supply,i} q_i(t) + C_{shortage,i} q_i(t)\right]\right\}$$

Where the subscript i represents the commodity and t the considered time-step in the simulation.

Its goal is to minimize the cost of meeting a given demand of energy services, with a trade-off between the supply cost of the required energy carriers and the cost of mismatching the energy balance (e.g. shortages).

The first term of the minimization represents the commodity cost, defined as the product between the specific cost per unit of required primary fuel (see Table 1) and the consumed quantity of this commodity in each time-step of the simulation. The second one instead represents the penalty cost for time-steps in which the availability of a fuel is not sufficient to cover its demand in the system, multiplied by the missing quantity of that commodity.

By considering this penalty cost, the model is allowed to conclude the optimization process even if there is an equilibrium mismatch in a single time-step. This enables to observe the presence of resources' scarcity and the system's condition in which they might occur. The resulting cost is then summed for each commodity and for each time-step of the simulation.

The problem is set in order that, for each time-step of the simulated period, the balance between production and demand is met for each commodity or energy carrier. These energy carriers are transformed through different processes, from the resources to the final commodities.

The decision variables of the optimization problem represent all the activities of the processes in the energy system. In order to better simulate the feasibility of a system, both technical constraints of the technologies (e.g. installed capacity, flexibility, efficiency) and physical limits of the system (e.g. resources' availability, storage capacity) are provided. Finally, demands are described through overall quantities and profiles.

The oemof structure is based on different logical components that are used to describe the reference energy system and build the optimization problem: (i) *buses* represent energy carriers or commodities; (ii) *transformers* represent technologies or processes consuming and/or producing one or more commodities (e.g. GT power plant where input natural gas returns output electricity); *source* and *sink* components are particular transformers used to represent respectively the introduction of commodities in the system (e.g. import of Natural Gas NG), and the demands of commodities (e.g. electrical load); finally, *storage* components enable to decouple demand and supply of a specific commodity, by storing the energy carrier for some time.

In NEMeSI these components are used to characterize the Italian energy system in 2050. Buses are used to represent energy carriers such as natural gas, hydrogen, electro-fuels, biomass, biogas, captured carbon dioxide, or energy carriers for final demands like heat and electricity.

Beside conventional power plants and cogeneration units, *transformer* class is used to describe electrolysis, catalytic and biological methanation, and the synthesis of electro-fuels. Except for biological methanation, all the listed P2X technologies present a potential for waste-heat recovery. The class of waste-heat recovery also includes methanol synthesis and power production via Fuel Cell (FC) technology.

The Organic Rankine Cycle (ORC) power generation technology, the direct air capture systems for carbon dioxide sequestration and the blending process for methane and hydrogen (with a maximum hydrogen content up to 20%vol), complete the list of *transformers* used in P2X section in NEMeSI. *Source* component is used to describe feedstock extraction/production (e.g. biomass, biogas, water for electrolysis) or for the overall supply (fossil natural gas). Import for hydrogen and electro-fuels is implemented with this class too, although in the tested scenario is not considered. Sources are used to describe the RES supply (e.g. wind, PV, solar thermal, etc.). *Sink* class is implemented for each synthetic fuel in addition to conventional electrical load and heating/cooling demands. Finally, in addition to thermal storage options, electrochemical and pumped-hydro storage, the *storage* component is implemented for representing the storage of hydrogen and other P2X products.

In Figure 1 a simplified version of the reference energy system is depicted, with a focus on the *Power-to-X* part. A complete explanatory scheme can be found in the attached material on the online version.

3. Case Study and Input Data

In this Section the main assumptions and input data of the model are presented, with a description of the tested scenario.

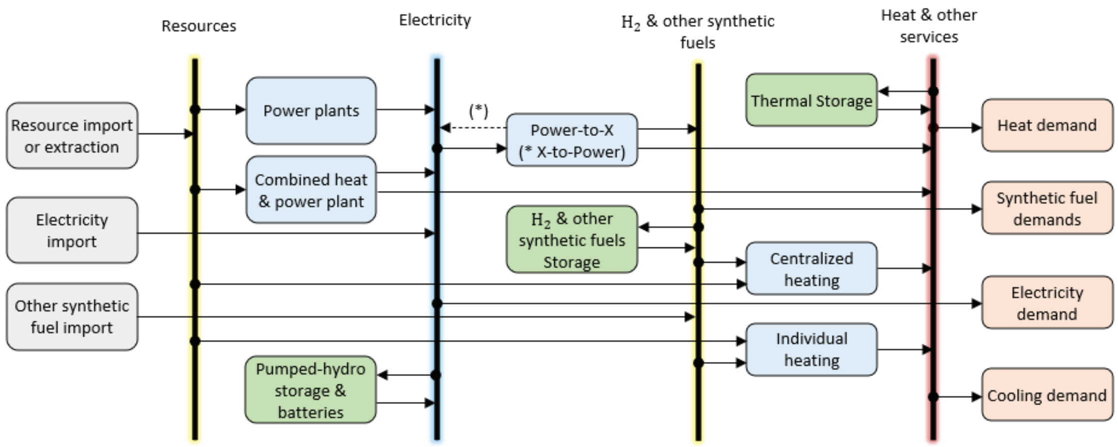

Figure 1: Simplified scheme of the Italian energy system (commodities and processes are aggregated for sake of representation) represented through buses (vertical lines), sources (grey boxes), transformers (light-blue boxes), storages (light-green boxes) and sinks (pink boxes).

The Italian energy system is modeled in a decarbonized scenario, with a single-node spatial resolution (the model does not consider inter-connections between bidding zones). Regional characteristics are not explicitly present in the model, although parameters from different zones are considered to obtain the aggregated dataset (e.g. for heating and cooling demands). Regional characterization of the system could represent future developments. The tested scenario chronologically simulates a single year, with an hourly time-step.

The rationale behind the scenario construction is based on reducing as much as possible the energy service demands in all end-use sectors (e.g. lower space heating demand in buildings through better thermal insulation) and preferring electrification and hydrogen-based solutions in order to meet the decarbonization target. Conventional power plants and fossil fuels utilization are limited to grid stability only, by coupling them with carbon capture and sequestration systems.

The presence of the latter is necessary to allow the system to use conventional fossil fuels for heat and power generation when strictly necessary (i.e. with a lack of RES or unavailability of energy from storages). The configuration of the energy system promotes the use of renewable sources, with a grid stability role for conventional power plants.

Penalties for carbon dioxide emissions or other societal costs (e.g. the cost for unpredictability of renewable energy) are not considered in the tested scenario. This because the aim is to investigate the configuration with optimal resources' allocation and to evaluate the self-sufficiency feasibility of the energy system. The introduction of these system costs could represent a valid future development to strengthen the analysis.

In order to pursue the rationale presented, in-depth evaluations were made through external analyses (e.g. simulation of an average yearly renovation rate in buildings), as well as through external policy indications (e.g. plans to achieve a shift from road to rail, and from the private to the public transport). All these assessments are out of the scope of this paper.

The scenario defines a decarbonized energy system which is mostly self-sufficient, except for electricity exchanged with border countries (higher electrification and RES penetration will likely strengthen the need of cross-border exchanges for a more efficient grid balancing) that is in lines with 2030 projections.

The only available fossil fuel is assumed to be natural gas, coupled with carbon capture and sequestration systems. Its availability was calculated from historical data [37]. For biogas availability, being the resource strictly limited by the amount of biomass that can be gasified, it is assumed to maintain the 2030 level [38].

A distinction has to be made between dispatchable and non-dispatchable RES. The installed capacity of hydroelectric and geothermal plants is the same defined for 2030 in the NECP [2]. Strong variations were assumed instead for wind and Photovoltaics (PV) installed capacity, due to their expansion potential. Generation capacity for wind is assumed to be 47 GW, while PV installed capacity is in the order of 300 GW. The latter is a really high value (roughly 15 times the current PV installed capacity), however these amounts consider the high energy amount required for P2X, the condition of almost total self-sufficiency of the energy system and are compatible with the results of previous research activities carried out within the authors' research group [39].

The possibility to import some synthetic fuel would determine a reduction of the e-fuels' demand covered by internal production, translating into lower electricity required by P2X processes. This could be translated in lower PV installed capacity, by far the highest value in the power generation mix.

The condition of deeper interconnection of the Italian energy system with border countries, which can be reasonable to expect in future, is not treated in the paper (except for electricity) but could be investigated in future analyses.

For conventional power generation and cogeneration plants, current installed capacities, reported by the Italian electricity TSO Terna [40] and by the annual report of the national Italian district heating association AIRU [41], were rescaled. Starting from the 24 GW of current combined cycle and gas turbine installed capacity and the 22 GW of cogeneration plants, values were rescaled, keeping the proportions defined in the 2030 version of the presented model [42], in order to meet the projected demands in the decarbonized scenario for the 2050.

The resulting values are considerably reduced, due to the limited use of natural gas with CCS and the wider RES penetration in the energy system. 4.5 GW for conventional power generation and roughly 19 GW for cogeneration plants are obtained.

Innovative technologies for *Power-to-X* were selected according to their Technology Readiness Level (TRL) or based on the interest the current market is showing. Being the P2X technologies structured as simple boxes (i.e. *transformers*) in the model, with input and output flows and defined parameters (e.g. efficiency, load flexibility), no modeling differences emerge between technologies that represent the same process.

The *transformer* implemented for the specific process might have different consumptions or load flexibility depending on the chosen technology. For example, to date, several electrolyzers and fuel cell options are under development but, for system modeling complexity issue, only one technology (Low Temperature PEM) was implemented in the model.

The same logic has been used for the option of power generation from waste-heat recovery via organic Rankine cycle. To date, several working fluids, with different properties and operation ranges, are studied. In this study two classes of waste-heat suitable for recovery are considered. Assuming to use only high temperature heat for power generation via ORC, from [43,44] a compromise solution for the technology (i.e. working fluid and cycle properties) was selected.

The implementation of this technology, which is not the most efficient way to generate electricity, in the system, is justified by the willingness to investigate all possible uses of waste-heat from P2X processes. The ORC solution again is represented as a single technology for system's modeling complexity issue in the case study.

Installed capacities for all P2X options were set in order to be able to cover final hydrogen and synthetic fuels demands (they were estimated after a first attempt simulation set, by considering load duration curves).

Focusing on P2X processes, in Table 2 the potentially recoverable waste-heat, divided by temperature range, are presented. A literature review was conducted to define the output heat from each process. However, for some P2L technology the literature does not provide sufficient information, due to the current low TRLs. It is the case of electro-jet-fuel synthesis. The same waste-heat recovery value of jet-fuel synthesis from biomass process was assumed, given the strong similarity in the production steps.

Two classes of heat sources are considered: High Temperature (HT) waste-heat sources and Low Temperature (LT) ones. The former represents all the P2X technologies where heat is produced with temperature above 150°C, while the latter includes temperature ranges between 50-90 °C.

Electrochemical storage and pumped-hydro storage, as well as thermal storage, were estimated as follow. Starting from the values defined in 2030 NECP projections, storage capacities were rescaled by considering the same proportion with respect to the RES installed capacity defined for the 2030 horizon. For example, given the generation capacity for wind and PV in the decarbonized scenario, 2050 horizon storage capacities are obtained for electrochemical batteries and pumped-hydro storage. For hydrogen and other electro-fuels, storage capacities were estimated in order to ensure the possibility of seasonal shifts.

Reasonable assumptions regarding energy demand values have been made taking advantages of the

Table 2: Potential waste-heat recovery for P2X processes, divided by temperature range.

Power-to-X sector	Technology	Generated waste-heat [MWh/MWh of product]	Waste-heat temperature	Ref.
Power-to-Gas	LT PEM electrolysis	0.135	Low	[6,7]
	Thermochemical catalytic methanation	0.245*	High	[12]
Power-to-Liquid	Methanol synthesis	0.560	High	[10,20]
	Fischer-Tropsch jet-fuel synthesis	0.266**	High	-
	Jet-fuel synthesis from methanol	0.266**	High	-
Biomass-to-Liquid	Jet-fuel synthesis from biomass	0.266	High	[10]
Power-to-X-to-Power	LT PEM Fuel Cell	0.330	Low	[3,6]
	Ammonia Fuel Cell	0.672	High	[45]

* the value does not include the heat required to self-sustain the process, which has already been subtracted

** due to lack of information, the authors assumed the value to coincide with potential waste-heat recovery of jet-fuel synthesis from biomass, being the production steps very similar

knowledge from previous works of the research group [39,46–48] .

For final demand profiles, starting from historical data, hourly trends are extrapolated for 2050 (i.e. by considering the evolution of power demand, the integration of intelligent heating systems etc.). For the charging profile of Electric Vehicles (EV), an intelligent behavior is assumed, referring to [49]. For a more complete definition of the case study see the Appendix 1 to integrate with the provided input dataset [34].

We stress once again that both demand and supply side are aggregated at national level, translating it into the possibility to have full flexibility for P2X plants: the limit on the load variation of a single installation is not seen when considering the aggregation of plants.

4. Results and Discussion

In this Section the main results on the behavior of the system are presented, with a focus on the recovered waste-heat from *Power-to-X* processes.

The assumption of very high RES penetration and the condition of domestic production of electro-fuels within national border translate into a very important amount of electricity (~340 TWh) spent on *Power-to-X* processes, largely provided by PV and wind mainly during overgeneration periods.

Figure 2 represents the annual profile for daily power generation and electricity demand. In the case study, conventional power generation and dispatchable RES ensure the minimum grid stability necessary to manage the wide fluctuations of non-dispatchable RES (namely photovoltaic and wind generation). However, these dispatchable power plants are able to cover only a part of the system's electrical load.

This is reasonable to expect, being assumed very high values for installed capacity of PV and wind power. The latter, with the help of electrochemical and pumped-hydro storage, cover the remaining electricity demand and the power destined for synthetic fuels production. *Power-to-X* is not supplied with excess electricity only, but it is evident from the graph that a consistent part of P2X is reasonably fueled via overgeneration.

As depicted in Figure 2, the overgeneration periods concentrate in the majority during the central period of the year (and of the day), thanks to a wider PV availability.

This electricity is mainly used for *Power-to-Gas* (roughly 85%), where hydrogen and synthetic methane are produced. A minor part (~7%) of the electricity is used in *Power-to-Liquid*. The *Biomass-to-Liquid* alternative is preferred, especially in jet-fuel synthesis, minimizing the need of electro-fuels and thus electricity. The model also considers the *Power-to-X-to-Power* solution (7%), by enabling power generation via Fuel Cell, while the remaining electricity for P2X is used for *Power-to-Heat* in DH networks.

Focusing on waste-heat, Figure 3 shows the high temperature waste-heat generation during the simulated year by P2X technology. Only technologies that are effectively used are plotted in the graph as result of the optimization process. An illustrative example can be found in jet-fuel synthesis. In the model three possibilities to produce jet-fuel are implemented, each of which generates

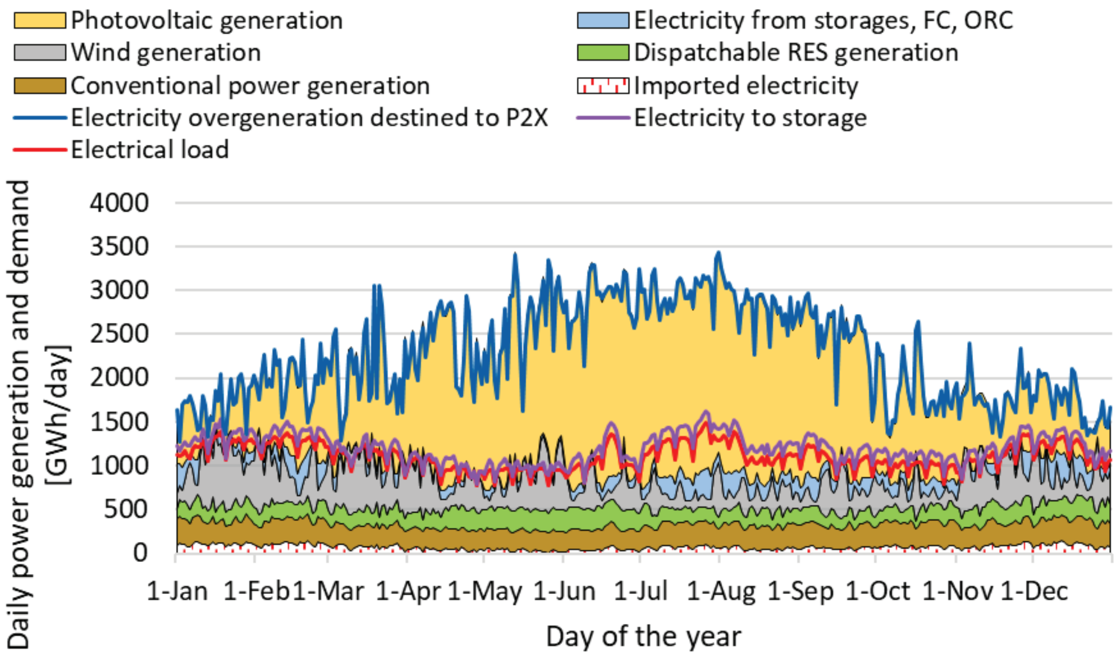

Figure 2: Annual profile for daily power generation and electricity demand; the former is represented by cumulative areas, the latter by cumulative lines; “dispatchable RES generation” includes hydroelectric, geothermal and bioenergy; “conventional power generation” includes gas power plants and cogeneration units; “electricity from storages, FC, ORC” includes electrochemical and pumped-hydro storages, fuel cell systems and organic Rankine cycles; “electricity to storage” represents the part of generated power that is stored in pumped-hydro or electrochemical systems; “electrical load” includes all final power consumptions for base load, EV charge, non-intelligent heating & cooling in civil sector; “electricity overgeneration destined to P2X” represents the excess electricity from power generation that is transformed into different energy carriers (e.g. hydrogen, electro-fuels).

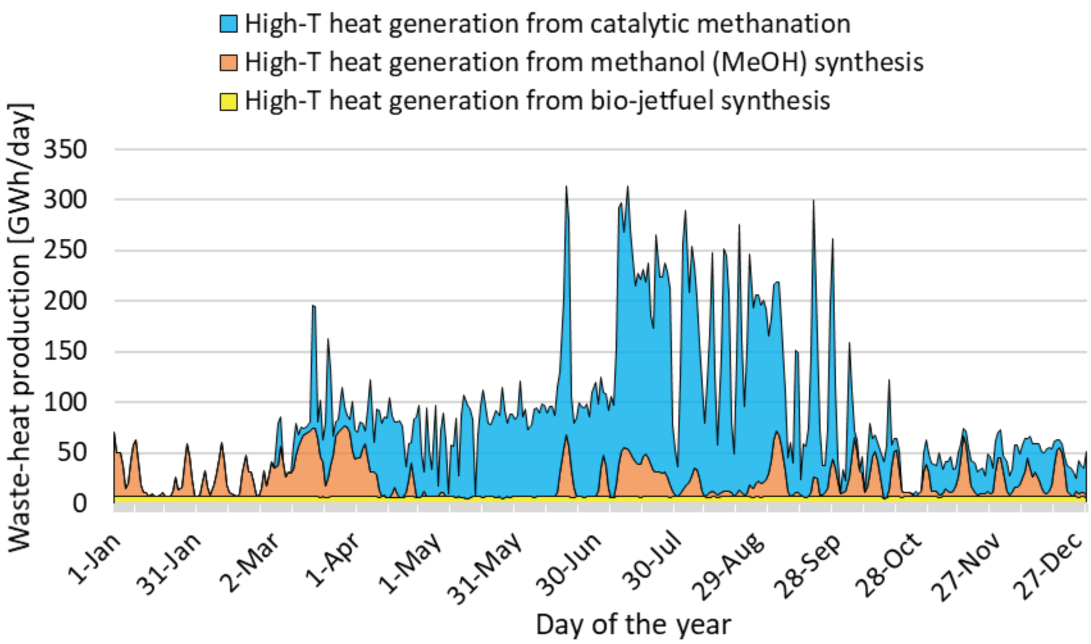

Figure 3: Annual profile for daily high temperature waste-heat production, divided by P2X technology.

HT waste-heat as by-product. However, the model gives preference to *Biomass-to-Liquid* pathway, due to feedstock availability and to overall higher energy efficiency.

In Figure 3 a roughly constant profile is reported for HT waste-heat generation from biomass to jet-fuel technology. This however represents only a minor part of the overall high temperature waste-heat generation, with two other processes with a dominant role. Methanol (MeOH) synthesis and thermochemical catalytic methanation represent almost the 92% of the HT waste-heat generated.

Methanol synthesis shows a rough periodical behavior during the year, thanks to the presence of high storage capacity, which enables seasonal fluctuations: MeOH production uses a major part of produced hydrogen in the period of the year where its availability is limited by low RES presence, as in the winter season. In Spring and Summer, higher PV and wind availability boosts hydrogen production, which is both stored and used as feedstock in other P2X processes. This can be observed in Figure 4, where hydrogen production and the different contribution of methane supply are presented.

Thermochemical catalytic methanation takes a central role during the Summer period, enabling the production and storage of synthetic methane and limiting the use of fossil origin's one, generating a high amount of recoverable HT waste-heat. The analysis returned a seasonal behavior for methane storage, which is used for those periods where RES availability is limited and conventional power generation plants are run as back-up.

The overall high temperature waste-heat recovery shows a potential of about 32 TWh during the simulated year. In Figure 5 the annual profile of the three HT heat uses is depicted.

From the presented graph seasonal behaviors can be identified. Between May and June, the model prefers not to use HT waste-heat since, with small exceptions due to unfavorable climatic conditions, no heating is required in civil sector in that period. Furthermore, those months are characterized by higher solar irradiation, with very high PV generation. The generation via Organic Rankine Cycle is then limited to night hours. During summer, there is a much higher HT waste-heat use in ORC power generation. This is due to a higher number of daily operating hours compared to the rest of the year.

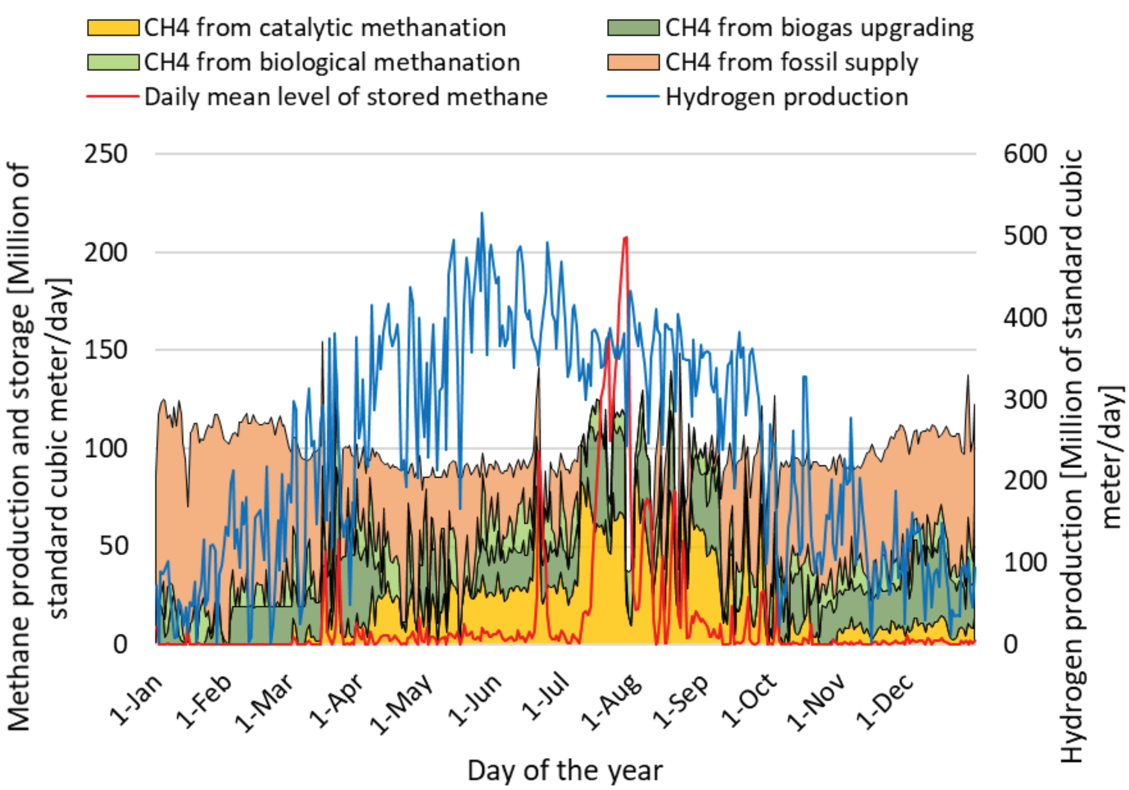

Figure 4: Annual profile for daily methane supply to the gas grid and daily mean level of stored methane (left axis) and daily hydrogen production (right axis); The level of stored methane represents the mean in-stock quantity over 24 hours per each day.

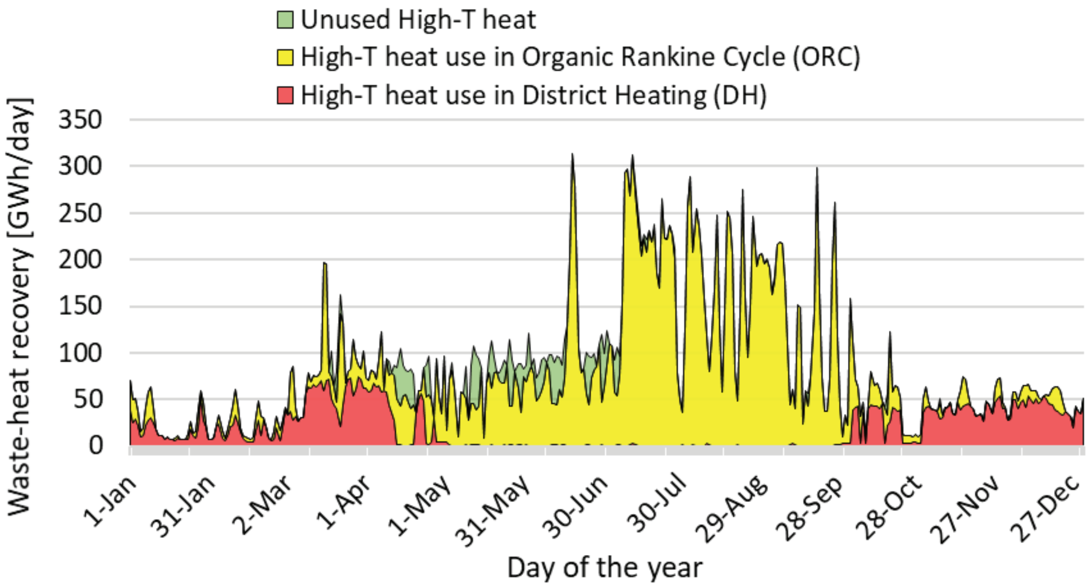

Figure 5: Annual profile for daily high temperature waste-heat uses.

In Autumn and Winter, there is a preference for district heating purposes, while power generation via ORC is limited to night hours again. It has to be stressed that the option of power generation from waste-heat recovery may result to be additionally promoted with respect to other conventional power plants (e.g. gas cycles). As presented in Section 2, the model setup optimizes the primary resources' allocation, by considering the supply cost for primary fuels as the only cost in the system. For this reason, waste-heat, that represents a by-product from P2X processes, can be considered as an additional free energy source and preferred with respect to other conventional solutions.

In analyses that would consider also other type of costs, for example operational ones, the use of waste-heat in power generation solution via ORC might result too much expensive and be less favored with respect to other destination.

In this scenario almost the 20% of high temperature waste-heat (roughly 6 TWh) is recovered and used in DH networks. This heat source covers more than the half (52%) of the heating for space heating and Domestic Hot Water (DHW) provided by DH. However, its use in DH networks significatively varies during cold season.

In Figure 6, a comparison between the coldest week of the year and one week in Autumn is depicted. The two graphs show the hourly profile of the heat supply in district heating networks divided into two categories: heat from conventional DH plants (e.g. cogeneration plants, industrial excess heat, urban waste incinerators) and waste-heat recovered from P2X. During the coldest period of the year, the recovered waste-heat mainly comes from methanol synthesis, but it covers just a minor part of the heating demand in DH systems, provided instead for the majority by conventional units.

The situation is different during the mid-season, when both the higher RES availability and the higher waste-heat recovery from P2X processes allow to supply most of the required heat in DH networks (Figure 4, right side) instead of conventional units, except for night hours, when HT waste-heat is used for power generation via ORC. No uses are modeled for low temperature waste-heat generated. The model however returns some indications about the related potential recovery. In Figure 7 cumulative daily values for LT waste-heat generation processes are reported, showing a high potential for low temperature class, with a dominant role of hydrogen production.

This second type of waste-heat could find application in such systems where the heat source's temperature is too low for a direct use and it would require a regenerative system (e.g. in DH units with upgrading systems). The implementation of this solution could be a possible improvement of the presented study.

Table 2 summarizes the waste-heat generation and utilization potentials, divided by temperature.

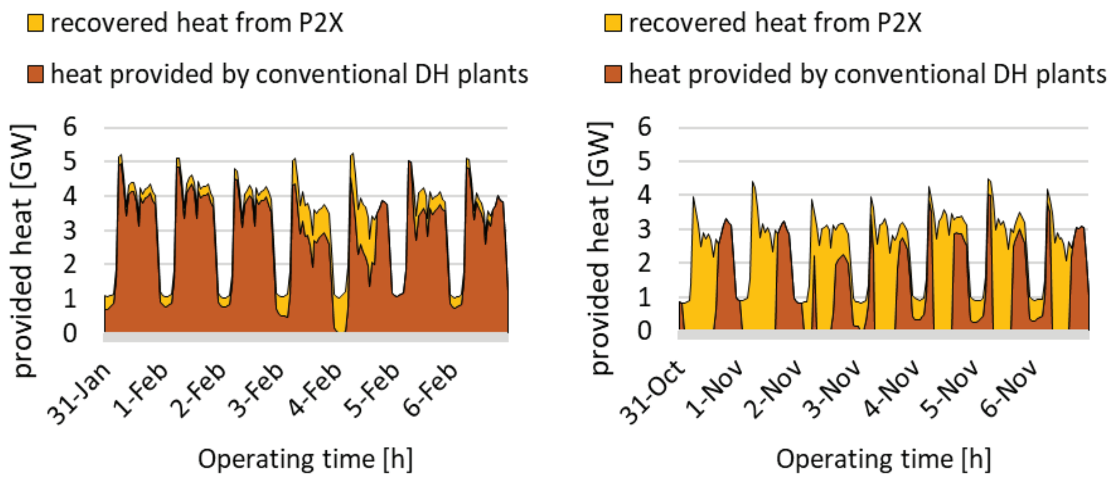

Figure 6: Comparison of supply heat profiles in district heating networks; in the left side a week of the coldest period of the simulated year is illustrated. In the right side, a weekly profile in Autumn is presented.

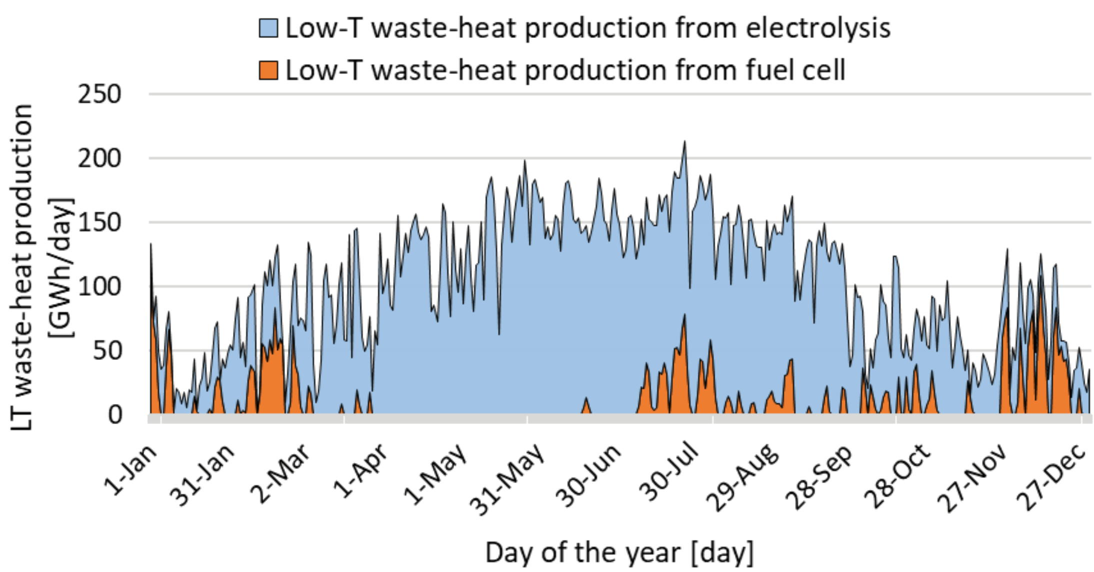

Figure 7: Annual profile for daily low temperature waste-heat production, divided by P2X technology.

Table 3: High temperature waste-heat production divided by P2X process and its utilization, plus low temperature waste-heat production.

HT waste-heat source [TWh]		**HT waste-heat destination [TWh]**	
Thermochemical catalytic methanation	23	Power generation via Organic Rankine Cycle (ORC)	22.9
Methanol synthesis	6.1	Direct use in DH networks	6.7
Fischer-Tropsch fuel synthesis	0	Unused	2.1
Jet-fuel synthesis from methanol	0		
Jet-fuel synthesis from biomass	2.6		
Ammonia Fuel Cell	0		
Total HT waste-heat [TWh]		**31.7**	
LT waste-heat source [TWh]			
LT PEM Fuel Cell		4.4	
LT PEM electrolysis		33.3	
Total LT waste-heat potential [TWh]		**37.7**	

5. Conclusions

The aim of the paper was to evaluate the potential of waste-heat recovery from *Power-to-X* processes in a decarbonized scenario. The presented case study described the Italian energy system in a long-term time horizon (e.g. 2050), with a single-node spatial resolution, pursuing a net-zero GHG emission target.

For this purpose, a literature review for understanding the waste-heat associated to the main P2X technologies was conducted and an energy system model was developed by the authors, able to simulate the different flows within the energy system. The analysis showed the generation of more than 30 TWh of waste-heat for both high temperature (31.7 TWh), and low temperature (37.7 TWh), the sum of which corresponds roughly to a quarter of the total heat demand in civil sector for space heating and domestic hot water.

The modeling of recovery focused however only on HT, for which three possibilities are considered: a direct use in district heating networks, a use in power generation via organic Rankine cycle or its simple dissipation in the environment. The use in power generation was preferred in periods of the year with low RES availability (night hours in cold seasons), or during summer, with higher number of daily operating hours compared to the rest of the year. The direct use in DH networks is then preferred during winter season.

HT waste-heat recovery covers a significant part (52%) of the total heat demand provided by district heating, although in the coldest period a strong integration with conventional units would result necessary. Seasonal behavior in hydrogen and methane synthesis can be observed, with production peaks in summer period, thanks to higher RES availability. PV and wind, as well as other RES, are assumed to have a deep penetration in the energy system and this translates into power grid unbalances and concentration of some P2X processes in specific periods (e.g. catalytic methanation during summer).

Although the analysis focused on high temperature waste-heat recovery, the model showed an important potential for LT waste-heat recovery too. Further developments might include its use for district heating purposes, considering the different recovery solutions (low temperature heat must likely be upgraded, depending on the network temperature). Possible improvements of this work include improving a more detailed spatial resolution (i.e. multi-node configuration), with better characterization of regional differences within the country. This would allow a better distribution of power generation installed capacity, the possibility to differentiate final demands taking into account local climatic conditions or bottlenecks in the transmission (e.g. power grid). The limit on plants' flexibility and seasonal storage option for district heating, as for as the evaluation of different cost types (e.g. investments, emission penalties etc) in the optimization, should be further investigated.

This research was a preliminary work aimed at exploring a possible future option of sector coupling which, to the knowledge of the authors, is poorly investigated in literature. The resulting high potential suggests future more in-depth analyses on the topic.

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Appendix 1: Description of Input Dataset

In the present Appendix, additional information for the dataset used to build the case study are provided. For a complete characterization of the profiles see the documentation provided in [34].

Final demand and power generation profiles were estimated starting from 2013 historical data. The normalized profile of electrical base load is assumed to coincide with the series estimated for 2030. The latter is calculated starting from historical actual load data, from which consumption series for electric heating and cooling are subtracted, based on assumptions of the authors. The obtained series is then projected to the overall consumption expected in 2030 and in 2050.

Electric consumption profile for cooling in civil sector is obtained as an elaboration from 2013 air temperature and relative humidity of three Italian cities, as for the heat demand for space heating and domestic hot water for buildings. Future improvements with a more specific spatial resolution will enable to expand the characterization of the model to different regional zones of the Italian energy system. Heating demand in residential and tertiary sector for space heating met by district heating is obtained from a statistical model developed by the authors based on correlation between air temperature data, day of week, hour of day, and energy provided to households in a monitored district heating network.

Regarding to RES power generation profiles (e.g. PV, run-of-river hydroelectric, geothermal), series refer to historical hourly electricity production provided by the Italian electricity TSO Terna [40], that are upscaled to obtain the expected annual electricity production in the investigated scenario.

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