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Evaluating the value of photovoltaics in decarbonization scenarios: evidence from the Lombardy Region

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Abstract:
The review of national and international energy strategies forced by recent disruptive events emphasized the importance of developing tailored planning to pursue the increased decarbonization goals. Within this context, the presented article first describes the development of a bottom-up optimization tool tailored for the Lombardy region, in Italy. Then it evaluates different technology mixes to identify the optimal configuration to reach local decarbonization targets at minimum costs. The model has a solid spatial resolution and a wide range of technological options, and it is set to analyse the local energy system at the target year (2030). The work evaluates the response of the system to different decarbonization goals and is carried out by comparing the cost of an avoided ton of CO_2. A $CO_{2\text{-equivalent}}$ emission limit in line with the EU Fit-For-55 package returns a feasible solution with conventional technology options, such as thermal insulation, electrification, energy efficiency and a partial substitution of natural gas with biomethane. Electrification is strongly bound to the expansion of photovoltaics since the additional potential of other sources is negligible. However, at higher decarbonization targets, the cost of avoided CO_2 rises at unsustainable values. Analysis on resources' availability, utility scale photovoltaic power plants and on commodity prices investigate the possibility to overcome this limit and the main results emphasize their strong impact on final energy configuration mix. They suggest the need to promote new photovoltaic installation and increasing the photovoltaic availability by 1,5 GW (+12%) could reduce the cost of avoided CO_2 of about 16%.

Keywords:
Energy system modelling; oemof; bottom-up model; renewable sources availability; high spatial resolution.

1. Introduction

In recent months and years disruptive events have strongly driven the review of national and international energy strategies, to better suit decarbonization pathway with a focus on energy security. In the European Union (EU), more challenging targets are going to be set, by strengthening the importance of differentiating energy supplies. Existing National Energy and Climate Plans are going to be updated with new targets for 2030 set by the "Fit for 55" (FF55) [1] and the "REPowerEU" [2] packages, currently under discussion by EU authorities. In particular the FF55 sets the goal of a reduction of 55% of greenhouse gas (GHG) emissions compared to 1990 levels [3]. It introduces specific targets for each end-use sector: e.g., the upgrade of the European Emission Trading System (EU ETS), with the reduction of total emission allowances (-61%) compared to 2005 [1].
All these targets must be received by national and sub-national authorities, through the development of local plans. In Italy, also each Region (i.e., the highest sub-national administrative level), has the authority to implement specific policies regarding energy and climate themes, in compliance however with national standards.

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Within the mentioned context, energy system modelling plays an important role. It can help policymakers to study the decarbonization process of energy systems and to identify minimum cost pathways. Several optimization framework's approaches exist. Fodstad et al. [4] provide a review of the state of the art, with a list of several studies which compare different frameworks and identify possible future developments. They recognize the importance to evaluate interdependencies among energy carriers, focusing on the integration of new energy carriers (e.g., hydrogen) or infrastructures (e.g., carbon capture and storage), to better describe interconnections within the system (e.g., sector coupling). They underline the required trade-off between spatial and time resolution, due to the computational issue related to the high level of detail for both.

1.1. Aim of the paper and outline

Through the development of an optimization tool tailored for the Lombardy region, in Northern Italy, the local energy system is evaluated at a target year (2030), in which the decarbonization targets are reached at the least cost. Within this context, the aim of the study is to evaluate the role of renewable energy sources (e.g., photovoltaic) and energy carriers (e.g., biomethane) and their impact in the GHG emissions reduction process. Multiple configurations of the system are then analyzed, by varying resources availability and prices of commodities. Lastly the work focuses on how system costs are influenced by the variation of boundary conditions (e.g., GHG emission target).

In the remainder of the paper, Section 2 presents the structure of the tool used for the analysis, the setup and the main assumptions of the analyzed case study. The construction of baseline case and sensitivity analyses are reported in Section 3, followed by main results in Section 4, while main outcomes and further developments are summarized in the conclusion (Section 5).

2. Methodology

In this Section the structure of the model is first presented, followed by the main assumptions and the setup of the case study.

2.1. Mathematical model structure

The possibility to evaluate interdependencies among energy carriers (e.g., through a multi-node representation), coupled to its open-source behaviour, led the choice of oemof framework [5], an open-source energy system modelling framework written in Python that can create and solve optimization problems, for the presented work.

To build the structure of an energy system, oemof framework uses different logical components: (i) buses, (ii) transformers, (iii) sources and sinks and (iv) storages. Buses represent energy carriers and commodities, such as electricity, heat or fossil fuels. Transformers represent processes or technologies which consume and/or produce one or more commodities. For example, a transformer may represent a gas power plant, which receives natural gas as input energy carrier and produces electricity as main output. Sources and sinks are two subcategories of transformers, respectively used to represent the production/introduction of a commodity in the energy system (e.g., the import of natural gas) and the final demand of an energy carrier (e.g., the heat demand in the civil sector). The storage component enables the system to decouple demand and supply of a specific energy carrier (e.g., electrochemical batteries). Lastly, the exchanges of a commodity between buses and transformers are named flows.

The objective function to be minimized, which represents the system total cost, is expressed, in a simplified way, as follows in Eq. (1):

$$\text{system total cost} = \sum_{h}\left[\sum_{c}\left(flow_{c,h}\cdot varcost_{c}\right)+\sum_{t}\left(capacity_{t}\cdot invcost_{t}\right)\right] \qquad (1)$$

$flow_{c,h}$ is the flow of the commodity c at time-step h,

$capacity_t$ is the capacity of the technology/transformer t related to the investment,

$varcost_c$ is the variable cost of the commodity c,

$invcost_t$ is the investment cost of the technology t.

The constraints of the considered optimization problem guarantee the balance of energy carriers and the satisfaction of demand. Ad-hoc bounds that could be added to the problem might be GHG emission limits or availability of resources. The decision variables of the optimization problem represent the new installed capacity (investments) and the energy and/or mass flows within the energy system.

A point of strength of the framework is the modularity of its components, that can be replicated as many times as needed, in series or in parallel, to build the energy system, as will be presented in the following section.

2.2. Energy system structure and assumptions

The spatial resolution of the tool starts from the aggregation of those local administrative division with similar socioeconomic and environmental characteristics, and results in 17 local areas within the region.

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Each area presents differences on the environment (e.g., climatic conditions, morphology and use of the land) and on the economics (e.g., gross domestic production, index per capita, average yearly income). For each area, final demands for end-use sectors, resources' availability and technological options were defined starting from a high spatial resolution and a modular scheme of the energy system was then built. In Figure 1 a simplified graphical representation is shown. Note that the energy efficiency option is modelled as a source of heat in order to quantify heat demand that can be avoided with that solution.

The resulting structure is quite complex, being characterized by more than 6500 exchanges (i.e., flows) between processes and technologies. The complexity of the energy system determines an important computational effort.

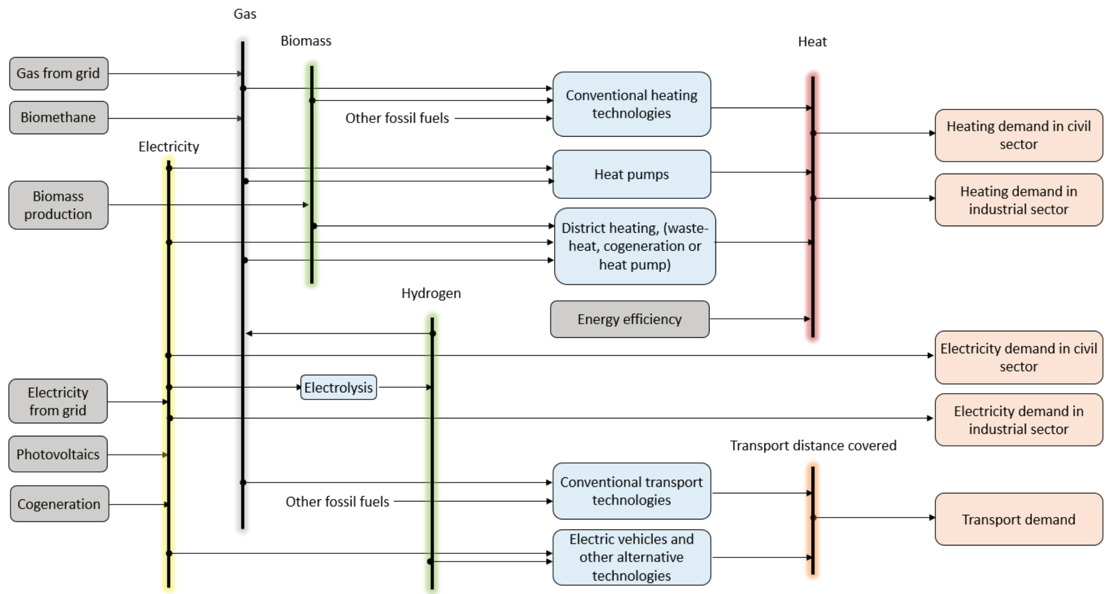

Figure. 1. Simplified scheme of the energy system for each area (commodities and processes are aggregated for sake of representation), represented through buses (vertical lines), sources (grey boxes, mainly on the left side), transformers (light-blue boxes, mainly in the central area) and sinks (pink boxes, mainly on the right); for sake of representation, other fossil fuels supply chain are not shown, as well as hydrogen blending process with natural gas.

Each technology or process is characterized by the following input parameters: (i) capital, variable and fixed costs; (ii) efficiencies, (iii) residual installed capacities in the years, (iv) availability or penetration limit of technologies.

Regarding the commodities and the energy carriers, the model considers: (i) natural gas, (ii) diesel, (iii) liquid petroleum gas for heating and (iv) for transport sector, (v) gasoline, (vi) electricity, (vii) solid biomass, (viii) biomethane, (ix) biodiesel, (x) hydrogen, and (xi) heat.

The end-use sectors are analyzed with different level of detail, strongly due to the availability of input data. The **civil sector** is the one with the highest technological detail, being investigated both the heating and cooling demand and the power demand. For each of the 17 areas, five types of building are identified, each one with its specific characteristics, to provide a realistic picture of the sector: (i) detached houses, (ii) apartment blocks for residential sector with an independent or (iii) a centralized heating system and (iv) tertiary buildings with independent or (v) centralized heating systems. For each one, the model provides different technological solutions to satisfy thermal needs, mainly: boilers, heat pumps, district heating from different sources (i.e., waste-heat from industry, natural gas or biomass fuelled dedicated plants, large size electric heat pumps). Also power self-generation by photovoltaics (PV) is considered in the civil sector. Different combinations of the PV technology (i.e., alone or coupled with an electrochemical storage) and final users (i.e., single users or energy communities) are considered.

Regarding the transport sector three main classes are considered: (i) light mobility, namely cars, with higher level of detail; (ii) light duty commercial vehicles, with an intermediate level of detail and (iii) other transport, which includes heavy road transport, naval and train, with a more aggregated description. For light mobility several technology options are compared: conventional propulsion systems based on internal combustion engines are in competition with plug-in hybrid electric vehicles or pure battery electric ones.

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The industry sector has very heterogeneous characteristics, about processes, technologies and energy carriers, which make it difficult to provide a detailed picture. The power and thermal final demands are investigated as aggregated. The supply options for the former are represented by electricity coming from the power grid or from self-generation through dedicated PV. Electricity can be used also to provide heating services, through industrial high temperature electric heat pumps or by synthetizing hydrogen through water electrolysis process.

Being out of the scope of the presented analysis, the conventional power generation of Lombardy (mostly made up of hydro and thermal power plants) is not explicitly depicted, but it is represented as a generic power grid, with an electricity source as component. Emphasis is indeed given to non-sectorial renewable energy sources, meaning those sources that are not exclusively dedicated to a single end-use sector. The first example is represented by PV at utility scale on dedicated surfaces and floating on quarry lakes. For biogas and biomethane, the study considers only the potential related to livestock residues and biodegradable municipal wastes. Ligneous biomass is considered in two different ways: sustainable local biomass and generic imported biomass.

With the resulting model, tailored analyses on resources' availability and on final demands of different energy carriers are then possible, by enabling policymakers to define ad-hoc policies, well suited for the local areas and in this way to adopt and apply on the territory national/international decarbonization strategies.

3. Input data

In this section the definition of a baseline configuration is presented in parallel with the construction of alternative options as sensitivity analysis. The optimal configuration of the system is defined throughout a range of emission reduction targets. This allows to test the optimal configuration in the neighbourhood of the decarbonization targets proposed by EU FF55 package (i.e., -44% vs. 2005, with total allowed emission equal to 43,5 Mt).
A 2030 baseline case is defined starting from a GHG emission-unconstrained energy system, a configuration to evaluate a pure economic optimization, to the minimum emission target allowed by given boundary conditions (e.g., resources' availability). In Table 1 the main input parameters are presented.

Table 1. Main input data for the baseline case (on the left) and for the sensitivity analyses (on the right); note that for each sensitivity analysis only the modified parameters with respect to baseline case are reported [source: elaborations from the authors].

			Baseline case	Modified parameters compared to baseline configuration		
			Medium commodity price	Low commodity price	High commodity price	Very high commodity price
Natural gas		[€/MWh]	95	60	137	179
Electricity	Cost for end-users	[€/MWh]	280	160	460	640
	Price sold to the market	[€/MWh]	140	30	250	386
			Minimum PV utility scale availability	Medium PV availability	High PV availability	Maximum PV availability
Installation capacity potential	PV total	[GW_e]	11,79	13,3	14,8	16,3
	of which PV utility scale	[GW_e]	*1,64*	*3,14*	*4,64*	*6,14*
			Maximum biomethane availability	Medium biomethane availability	Low biomethane availability	Minimum biomethane availability
Biomethane annual availability		[TWh]	11,5	9,7	7,8	6

PV total includes rooftop installation potential in civil sector, industry and utility scale plants (ground and rooftop based).

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In baseline case for PV utility scale only unused lands and coverage of quarry lakes are considered [source: elaboration of the authors on RSE [6]]; in sensitivity analysis, the potential of PV rooftop installation on public parking is added. Commodity prices are estimated from historical data (from 2013 to the first half of 2022); the configuration with very high commodity price considers the most recent period (first half of 2022); electricity values represent cost for end-users (first row), and the price of quantities sold to the power market (second row) [source: Italian Authority for the regulation of the energy, grid and the environment ARERA [7]]

For each configuration, the energy system is analyzed at different limits of emissions, each of which is independent from the others. The tool allows to identify the optimal distribution of cost effort (namely the required investments to reduce GHG emissions) between sectors. It returns an optimal configuration mix under specific assumptions, which are strongly related to the estimated evolution of parameters. Each sensitivity analysis presented below focuses on a specific topic. The structure and the assumptions of the energy system are the same of the baseline case, except for the boundary condition that is object of the analysis.

A first sensitivity study is driven on prices of electricity from power grid and natural gas. A second level of sensitivity concerns the availability of resources. Being wind power generation out of the scope (i.e., no potential is identified within the region) and being the installation of distributed PV plants difficult to be controlled by regional authorities, PV utility scale plants is selected. In the baseline case, a potential of 1,64 GW of new installation capacity is estimated for the utility scale PV, by considering available unused lands destined to regeneration and a potential surface coverage of quarry lakes. In the sensitivity analysis the role of potential PV installations on covertures of large size public parking is considered. Through the information provided by OpenStreetMap [8] and QGIS platform [9], open-source geographic database and geospatial data visualization tools, the available surface suitable for rooftop PV installations is estimated. Only parking spaces with a minimum surface area are considered and with assumptions on the eligible surface area to PV installation (e.g., lanes to manoeuvre might not be covered by rooftops) and on the share of total parking suitable for photovoltaics installation (e.g., in short-term large rooftop PV installation is more likely to occur on larger surface areas), a PV utility scale additional potential of about 4,5 GW_e is obtained.

Finally, some considerations can be made on biomethane. Being gas still an important energy carrier in base-case scenario (for example in civil sector, with a significant role in supplying heating systems), the switch from fossil-based gas to bio-based one is strongly promoted. Biomethane from biodegradable municipal waste and especially from livestock residues might be more difficult to be developed. A sensitivity analysis has then been conducted to evaluate lower potential, with a reduction of almost 48% in the worst case.

4. Results

This section returns and compare the main results, with an overview of the energy system first, and then by deepening the system total cost. In particular it presents the main comparison between present time, baseline case and the tested sensitivity analyses. Figure 2 shows the final consumptions, comparing the FF55 emission limit configuration (i.e., 43,5 Mt $CO_{2\text{-eq}}$) in 2030 vs. present time. The chart returns for every tested scenario an overall reduction in final consumption. Energy efficiency and the switch to less emitting technologies are the main drivers to pursue decarbonization targets.

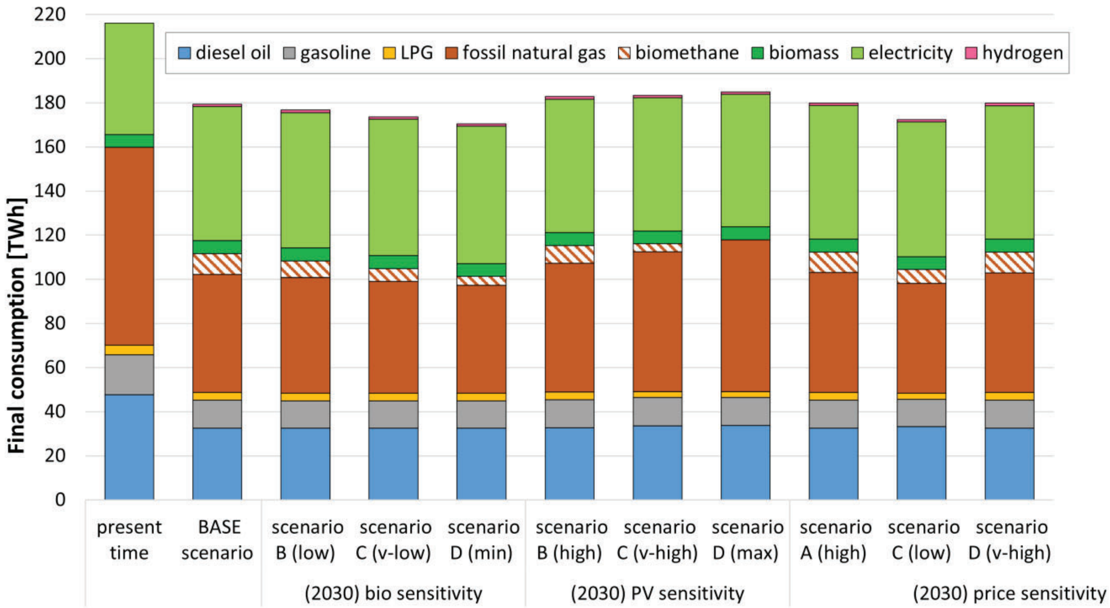

Figure. 2. Final consumption by energy carriers in different scenarios; v-low = very low; v-high = very high [source: elaborations from the authors].

For the baseline configuration a cumulative consumptions reduction of about 17% compared to present time can be observed. The most important contraction occurs in fossil natural gas consumption (-40%), thanks to the introduction of biomethane and to the electrification of different end-use sectors (+20%), such as space heating in the civil sector. The latter is interested by a strong consumption reduction through extended building refurbishments (up to 2% of the buildings/year, i.e., the maximum allowed), coupled with a strong electrification of the heat sector and the construction of district heating networks. Gas boilers keep playing an important role, with however a remarkable substitution with newer systems. The overall effect is a GHG emissions reduction of about 50% in civil sector, vs. 2005 levels. Regarding transport sector, there is a lower reduction in final consumptions (about 10%) between present time and 2030, mainly through the electrification of light road transport and the introduction of less carbon intensive solutions. The resulting configuration mix returns a reduction of about 35% of $CO_{2\text{-eq}}$ emissions in the sector vs. 2005 levels. Industry consumptions are reduced of about 18%, mainly thanks to the switch from gas to electricity.

By focusing on the sensitivity on RES availability, in case of biomethane reduction, an overall reduction of final consumption is observed compared to baseline one. Being PV installations, electrification option and building refurbishment in civil sector all completely exploited, more efficient options, such as electric heat pumps in DH networks or vehicles substitute conventional less efficient options (e.g., gas CHPs, fossil fuel-based vehicles). When the focus is on PV availability, the scenarios analyze the case of gradually additional PV capacity potential, by introducing new installation on rooftops of public parking. Electricity from PV can be self-consumed, shared between groups of local end-users (i.e., energy communities) or sold to the market. In every scenario the PV overall power generation is always at its maximum (about 11 TWh), although with different distributions in end-use sectors. Differences occur in installation of PV utility scale plants. As expected, in PV sensitivity scenarios, the increasing PV utility capacity potential is effectively installed, reaching a total PV electricity production nearly 15,8 TWh in maximum case. The last sensitivity analysis focuses on the price of gas and electricity. In the scenario with low prices the main output is an overall final consumption reduction. The lower cost of gas enables a more widespread use of conventional gas boilers in civil sector (both old and new models) at the expense of electrification and gas CHPs in DH networks. In the scenarios with high and very high commodity prices energy efficiency gains importance (e.g., gas heat pumps in substitution of conventional gas boilers).

To complete the description of the energy system, it might be useful to focus on the cost of the avoided GHG emissions, expressed in €/t_{CO2} avoided. This cost is defined as the ratio between the difference of the system total cost and the difference of total GHG emissions. The former is obtained as the sum of the total cost of annualized investment plus the operation cost of the target year. In Figure 3 the different trends of the cost of avoided GHG emissions are presented, both for biomethane availability (blue lines) and for photovoltaics one (green lines).

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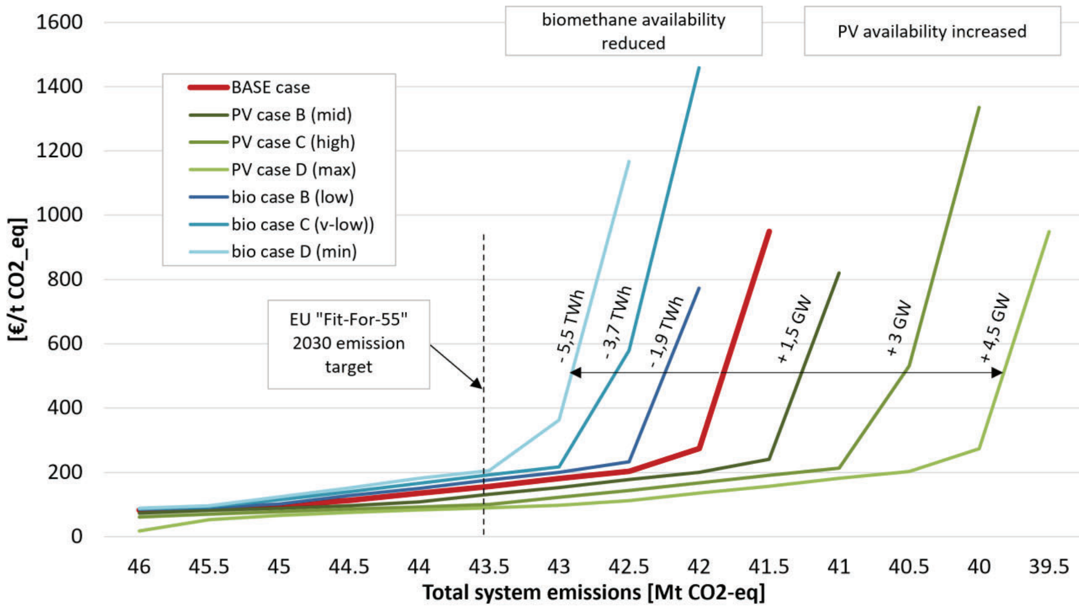

Figure. 3. Comparison of costs for avoided $CO_{2\text{-eq}}$ emissions between 2030 baseline scenario (red line, in the middle) and sensitivity on biomethane availability (blue lines, on the left) and PV availability (green lines, on the right); on X-axis the system total $CO_{2\text{-eq}}$ emission levels are reported, in line with Fit-for-55 package (with the target of 43,5 Mt); v-low = very low [source: elaborations from the authors].

Starting from PV, the graph shows that, at increasing installed PV capacity, it is possible to reach lower total system emission levels. The system's total cost of avoided GHG emissions can be kept at reasonable values in more challenging configurations. Similar trends can be observed in the sensitivity analysis of biomethane availability. The analysis investigates the effect of a less developed biomethane supply-chain. By reducing its availability in the energy system, the minimum emission limit (i.e., the physical limit for the configuration, given its boundary conditions) of the system shifts at higher levels. For both PV and biomethane case, the graph seems to identify a cost range (around 200-270 €/$t_{CO2\text{-eq avoided}}$) above which getting an additional reduction of the system's emission unit becomes economically not viable. In both sensitivity analyses, at the target of 43,5 $Mt_{CO2\text{-eq}}$, differences between costs are still quite limited, meaning that the configuration is not close to the technical limit (at given boundary conditions), except for case of minimum biomethane availability.

Last sensitivity analysis concerns the different prices of commodities. As expected, the variation of commodity costs has an immediate effect on the overall system total cost at every tested GHG system emission level. The differences between scenarios widen as the emission limit is reduced. At the target of 43,5 Mt of $CO_{2\text{-eq}}$ high and very high cost scenarios show an increase of about 97% and 199% compared to base-case levels (around 190 €/$t_{CO2\text{-eq avoided}}$), while a reduction of about 32% in minimum cost configuration can be observed.

5. Conclusion

The presented work aimed to study a possible optimal energy mix for the Lombardy region at the target year 2030 and to evaluate the weight of specific input parameters (e.g., resources' availability, commodity prices) on its composition. In a scenario in line with EU Fit-for-55 package, useful consideration emerged for local policymakers. The process of decarbonization takes place through a combination of electrification of final consumption and improvements thanks to energy efficiency. PV and building refurbishment options are exploited in every tested scenario at their maximum. The GHG emission reduction evolution is mainly driven by civil sector and transport one (-50% for the former, -35% for the latter compared to 2005 levels). Sensitivity analyses were conducted to evaluate the role of (i) commodity prices, (ii) PV potential installation capacity and (iii) biomethane availability.

Regarding the cost of electricity from the power grid and of natural gas, in high-cost scenarios energy efficiency gains importance and enables the introduction of technology options that would otherwise remain excluded by the market (e.g., gas heat pumps in civil sector). Sensitivity analyses on biomethane and PV utility scale seem to suggest the existence of a range of system's total cost of avoided GHG emissions around 210-270 €/tCO2-eq avoided, above which the further emission reduction would become economically unviable (at given boundary conditions). The increase (or the decrease) of RES availability shifts at lower (or higher) minimum GHG emission levels the energy configuration mix.

The main advantages of the developed tool are its replicability and its suitability to evaluate different energy systems, with a free level of customization on technological and spatial level. Further development might couple the results of the tool with frameworks with higher time-resolution, for example to better evaluate infra-day or day/night fluctuations both in demand and supply.

Nomenclature

CHP Combined Heat and Power plant

DH District Heating

ETS Emission Trading System

EU European Union

FF55 Fit-For-55 package

GHG Greenhouse gas

PV Photovoltaics

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