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ORIGINAL PAPER

The potential role of biomethane in the transition towards low-carbon large-scale buildings: the case study of the Torino airport

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Abstract

Biomethane represents an interesting solution for the growing pool of energy-intensive companies that are reducing their greenhouse gas emissions. Biomethane may help in the transition from fossil natural gas. Nonetheless, its inclusion in decarbonisation strategies is hindered by uncertainties around its future availability, price, and net environmental impact. This study aims to assess how these uncertainties affect the potential role of biomethane in the energy transition, investigating the specific case of Torino Airport. To explore the dynamics related to the use of biomethane, an energy system optimisation model is employed, to simulate cost-optimal development pathways under alternative prices and emission factors scenario. The results show that the potential availability of biomethane at an affordable price would significantly accelerate the energy transition of the airport. In particular, biomethane is key for strategies based on fuel cells, smoothing the transition from natural gas to an hydrogen supplied system. Nevertheless, price uncertainties still remain, for mid-terms projections, and these were found to significantly affect the operational expenditures, while the potential unavailability of the supplies could significantly jeopardise the airport environmental commitments. In this regard, pathways relying on a combination of different measures, such as electrification, proved to be more resilient to future potential discontinuities in green energy supplies.

Keywords Energy system model · Energy transition · Hydrogen · Airport · Biomethane

Introduction

In the aftermath of the 2022's energy crisis, biomethane rose to a core position in the European energy transition strategy. The REPowerEU plan (Commission 2022) was issued by European Commission to support the resolution to increase renewable generation in the region, with the dual scope to curb greenhouse gas emissions and reduce the dependency on fossil fuels imports. The plan envisages a special role for biomethane, proposing to scale up the production capacity from today's 3 billion cubic metres (bcm) per year to 35 bcm by 2030, which would cover the 23% of European natural gas import from Russia in 2021 (Eurostat 2023).

In Italy, the latest update of the national energy and climate plan (dell'Ambiente e della Sicurezza Energetica 2023) sets an ambitious target of nearly 6.0 bcm biomethane production per year—about 9% of the national gross natural gas demand in 2020 (dello Sviluppo Economico 2020). The development of the biomethane value chain is primarily supported by the Ministerial Decree 15/9/2022 (della Transizione Ecologica 2022), which established an incentive scheme to promote the creation of a market for biomethane. According to this scheme, producers can feed biomethane into the gas grid, receiving one *Guarantee of Origin* (GO) for each injected MWh, which can be traded on an apposite market platform. Through the purchase of a GO, final users can virtually claim the renewable origin of the gas withdrawn from the grid. This 'book-and-claim' chain of custody is fairly uncommon in the alternative fuels sector; however, in the Italian context, it is justified by the physical segregation enabled by the widespread natural gas grid and offers a significant simplification to the development of a market for this product. In fact, the success of similar incentivise schemes entirely depend on the creation of an effective

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market for biomethane GO. These could find willing buyers in the growing pool of energy-intensive companies which, mandated by law or on a voluntary basis, are seeking to reduce their emissions (Agosta et al. 2023). Replacing their current natural gas consumption with biomethane, whose properties are almost indiscernible from fossil natural gas, could contribute to these reduction targets without requiring major modifications of the energy system. In addition, the possibility to virtually withdraw biomethane from the existing natural gas grid, through the purchase of GO, would make this solution available to large energy consumers at no upfront cost.

Despite these advantages, the inclusion of biomethane in industries' decarbonisation strategies is associated with several uncertainties, in particular concerning its future availability and price differential with the fossil counterpart. Despite the projected increase in production capacity, biomethane will remain a resource potentially limited by the availability of sustainable feedstock. In addition, with emissions reduction targets becoming more stringent in the next years, it can be expected that larger shares of this fuel may be diverted to heavy-duty industries (steel, cement, etc.) and potentially transport (Bataille et al. 2018). These sectors, for which electrification is often a more complex option, will be willing to pay a higher price for biomethane, likely driving the market price for the GO. Another source of uncertainty concerns the environmental benefits of biomethane which, when looked from a lifecycle perspective, can offer extremely variable performances, depending on the feedstocks and the process used for its production (et al. 2020; Parliament and Council 2018; Prussi et al. 2020; Tonini et al. 2016).

From an academic perspective, biomethane has been extensively investigated in terms of sustainable feedstock availability, production pathways, and lifecycle environmental performance, with studies highlighting a wide variability of greenhouse gas emission factors depending on the substrate and process configuration. At a system level, several contributions have assessed its potential role in national and regional energy transitions, often focusing on supply-side constraints and competition with other hard-to-abate sectors such as heavy industry and transport. However, comparatively little attention has been paid to the demand-side integration of biomethane within local, multi-energy systems, particularly under market-based instruments such as Guarantees of Origin and book-and-claim schemes. Existing energy system optimisation studies applied to airports and other large infrastructures predominantly address electrification, on-site renewable generation, or hydrogen deployment, while the role of renewable gases is either marginal or treated deterministically. As a result, the combined effects of biomethane GO price uncertainty, lifecycle emission variability, and interaction with emerging hydrogen technologies on cost-optimal energy system design remain insufficiently explored. This work addresses this gap by applying an energy system optimisation framework to assess biomethane as a transitional decarbonisation option for an airport energy system, explicitly accounting for economic and environmental uncertainties and their implications for long-term infrastructure decisions.

The scientific aim of this work is to assess the role that biomethane can play as a transitional energy carrier in the decarbonisation of airport energy systems under conditions of economic and environmental uncertainty. The subject of the research is the energy system of Torino Airport, which currently relies on natural gas for a significant share of its final energy demand and plans the deployment of a fuel cell-based trigeneration system as part of its decarbonisation roadmap (SAGAT 2024). To achieve this aim, the study applies a bottom-up energy system optimisation model to identify cost-optimal development pathways under alternative scenarios for biomethane Guarantees of Origin prices, lifecycle emission factors, and the availability of an external supply of green hydrogen. The analysis focuses on the interaction between biomethane uptake, electrification of heating, and fuel cell deployment, as well as on the robustness of different decarbonisation strategies to future uncertainties.

This study extends the existing research on airport decarbonisation and renewable gas integration by explicitly modelling biomethane as a demand-side decarbonisation option within a local multi-energy system, accounting for market-based instruments and lifecycle emission variability. In doing so, it provides novel insights into the conditions under which biomethane can effectively support the transition from fossil natural gas to hydrogen-based energy systems in large, energy-intensive infrastructures. The study applies an energy system optimisation approach to determine under which conditions biomethane could become an integrated part of the airport energy supply. The model is employed to produce cost-optimal pathways, under alternative future scenarios. The designed scenarios aim to capture the uncertainties related to biomethane GO price, emission factor, and, additionally, to the availability of an external supply for the green hydrogen (Sauhats et al. 2016). The energy system configurations provided by the model are then investigated in terms of installed fuel cell capacity, electrification rate, and biomethane uptake. Moreover, representative system configurations are selected and the additional economic and environmental costs, that the airport would incur under different future scenarios, are quantified.

Materials and methods

The methodological framework adopted in this study is based on a bottom-up energy system optimisation approach, which is widely used in the literature to investigate cost-optimal decarbonisation pathways under multiple technological and policy constraints. Compared to simulation-based or accounting methods, optimisation models allow the endogenous selection and sizing of competing technologies, ensuring internal consistency between investment decisions, operational strategies, and emissions targets (see Fig. 1). This feature is particularly relevant for airport energy systems, where long-lived infrastructure investments and interacting energy vectors (electricity, heat, gas, and hydrogen) must be jointly considered.

The optimisation model represents the current energy system of Torino Airport and a set of candidate technologies available for its decarbonisation, including renewable generation, electrification options, and gas-based solutions. A cost-minimisation objective function is adopted, subject to technical, operational, and environmental constraints, in line with established energy system modelling practices for local-scale applications. This formulation enables the identification of cost-optimal development pathways capable of achieving the airport's emission reduction targets while preserving energy supply reliability.

Uncertainty related to the future role of biomethane is addressed through a scenario-based approach, which is commonly employed in energy system studies when key parameters are characterised by high uncertainty and limited predictability. In particular, alternative trajectories for biomethane Guarantees of Origin prices and lifecycle emission factors are defined to reflect the combined effects of feedstock availability, competition with hard-to-abate sectors, and variability in production pathways highlighted in the literature. Treating these parameters as exogenous scenarios, rather than endogenous model variables, allows a transparent and systematic exploration of their influence on optimal system configurations.

In addition, dedicated scenarios are introduced to represent the potential availability of an external supply of green hydrogen. This modelling choice reflects the current uncertainty surrounding hydrogen infrastructure development at the local level and avoids speculative assumptions regarding future production costs and network expansion. The scenario-based representation allows the analysis to isolate the interaction between biomethane uptake, electrification, and hydrogen availability in the airport energy system.

For each scenario, the model computes a cost-optimal development pathway, defined as the sequence of technology investments and operational decisions that minimise total system costs over the analysis horizon. From the full set of results, representative system configurations are selected and subsequently evaluated under alternative scenario assumptions. This second step enables the quantification of potential economic and environmental penalties associated with pathway lock-in, thereby providing insight into the robustness of decarbonisation strategies in the presence of future uncertainty.

The remainder of the paper is organised as follows. Section 2 describes the methodological framework adopted in the study, including the energy system optimisation model, the Torino Airport case study, and the design of alternative future scenarios for biomethane price, emission factors, and hydrogen availability. Section 3 presents and discusses the results of the analysis, focusing on the cost-optimal development pathways of the airport energy system and on the implications of biomethane integration under different scenario assumptions. Finally, Sect. 4 summarises the main findings of the study, discusses their implications for airport decarbonisation strategies, and outlines directions for future research.

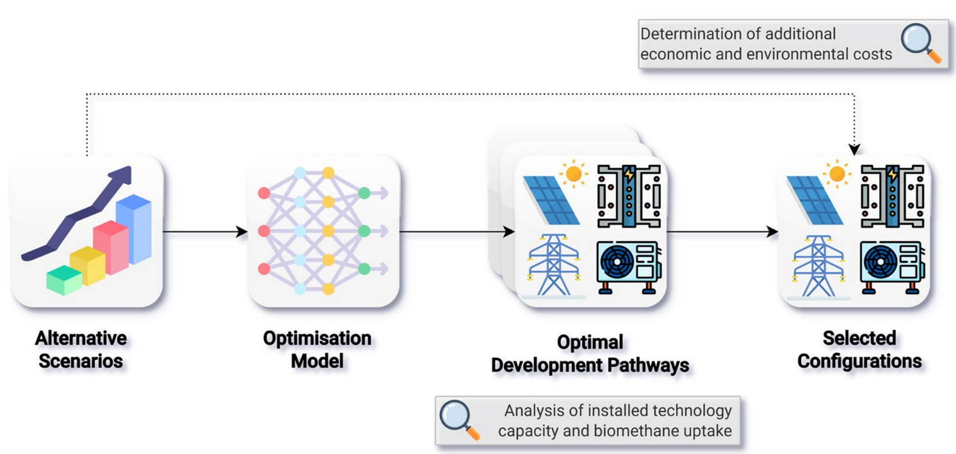


Fig. 1 Illustration of the methodology applied throughout the study

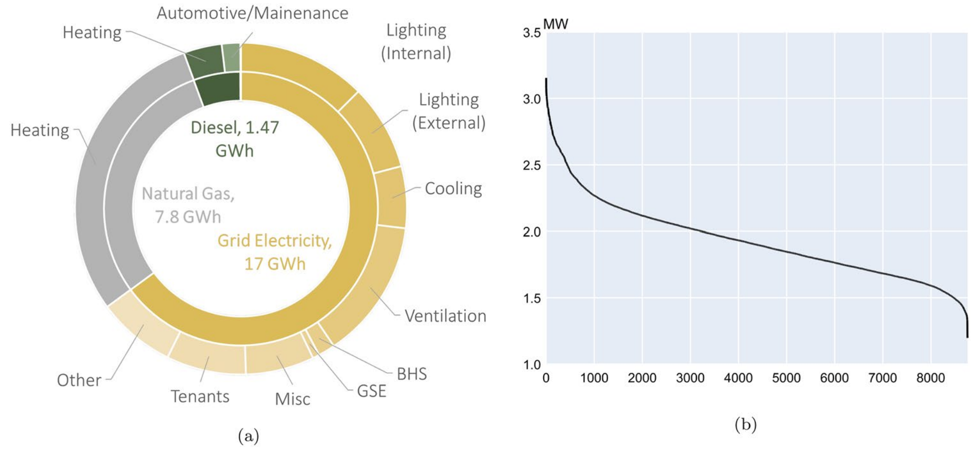


Fig. 2 **a** Consumption of the three main energy vectors in use at the airport and breakdown of the energy demand by service. **b** Hourly load curve of the airport's electricity demand. Data refers to year 2019. Source: SAGAT

The Torino Airport case study

Torino Airport is a large regional airport, situated in Northern Italy, few kilometres from the city of Turin. During the 2019, the year before the COVID-19 crisis, air traffic accounted for more than 40'000 flights and nearly 4.0 million passengers. After the drop that affected the aviation sector worldwide, due to the COVID pandemic, the airport activities rapidly recovered, establishing in 2023 a new record for the number of passengers (4.5 millions).

Looking into the energy system, the airport consumes mainly three types of energy carriers for its operation: electricity, natural gas, and diesel (Fig. 2a).

Electricity generation at the provincial or regional level is not explicitly modelled in this study. Instead, the airport is represented as a demand-side actor connected to the national electricity grid, whose carbon intensity and price evolution are exogenously defined based on national projections. This modelling choice is consistent with the objective of assessing local energy system design decisions, rather than power system operation or generation mix optimisation.

The airport has a high electricity baseload, with power demand rarely below 1.5 MW (Fig. 2b); typically, power demand ranges between 1.5 and 2.3 MW. Spikes above 3.0 MW have been observed and are typically associated with cooling in hot summer days. Further details on the airport energy system have been discussed by the authors in a previous publication (Prussi et al. 2023).

It is relevant to remark that the Torino airport has long been involved in reducing its environmental footprint: in the medium term (2030), it plans to reduce its emissions by 55% with respect to 2010 levels, with the ultimate goal to reach a net-zero emissions energy system by 2050.

The energy system optimisation model

An energy system optimisation approach has been employed to study cost-effective development pathways of the airport under different scenarios. This family of models determine the optimal configuration of the system, performing investment and energy dispatch decisions, under a pre-defined set of technical, economic, and environmental constraints (Groissböck 2019). The optimum is most often defined as the minimisation of the total system discounted costs, over the modelled period. The results of the optimisation therefore correspond to the configuration of the system which presents the lowest cost, according to a Net Present Value (NPV).

In this study, Torino Airport's energy system was modelled using OSeMOSYS, the Open Source energy MOdelling SYStem framework (Howells et al. 2011; Welsch et al. 2012). The framework was selected following an extensive review of the open source modelling landscape conducted by the authors, as presented in a previous work (Laveneziana et al. 2023). In OSeMOSYS, the mathematical optimisation problem is based on Linear Programming (LP), with the possibility to switch to Mixed Integer Linear Programming (MILP) for selected constraints. The model is implemented in the GNU MathProg programming environment. The commercial CPLEX solver was used to solve the optimisation problem.

OSeMOSYS is based on a multi-year investment approach, which makes it particularly suitable to model the transition of energy systems. All the input data can be expressed as year-dependent, providing flexibility in the design of future scenarios. Moreover, the model allows to impose emissions reduction trajectories to the energy system, enabling the study of decarbonisation pathways. The following paragraphs detail key assumption on the model developed for Torino Airport.

The energy model of Torino Airport was realised in the context of the *TULIPS - Green Airports* project.[1] The modelled system includes the main airport activities, such as

[1] https://tulips-greenairports.eu/

space heating, cooling and lighting, company cars, ground support equipment, and various other electricity consumption items. Figure 3 shows an excerpt of the energy system model under study, highlighting the aspects which are more relevant to this work.

The core of the energy system is represented by a microgrid concept featuring on-site photovoltaic (PV) generation, battery and chemical storage technologies, and a Combined Cooling, Heat and Power (CCHP) system, with a fuel cell as prime converter. The most innovative part of the system is the Solid Oxide Fuel Cell (SOFC), based on the commercial equipment developed by FuelCell Energy (Energy 2024). The SOFC can by fed with different blends of natural gas (or biomethane) and hydrogen, up to 100% hydrogen. Being a high-temperature fuel cell, waste heat is produced and can be exploited for heating or, when coupled with an absorption chiller, cooling purposes.

Excess PV electricity generation can be injected back to the grid or stored on site. Two storage technologies are considered: a 0.25C Li-ion battery and hydrogen production. Hydrogen is produced from a Proton Exchange Membrane (PEM) electrolyser, compressed and stored in a hydrogen vessel at 300 bar. To complete the analysis, both the hydrogen and biomethane can be supplied externally (depending on the scenario examined) from the airport. Hydrogen can only be used to feed the fuel cell, whereas biomethane can also replace current natural gas consumption for other services. In the technology solution space implemented in the model, the space heating demand, presently satisfied by natural gas and diesel boilers, can also be electrified through air-to-water heat pumps (A2W HP).

The implementation of the airport energy model required several assumptions concerning technology price and performance, as well as their evolution over the next years. Fundamental techno-economic details can be found in Appendix A. The full dataset is made available upon request, with the exception of confidential information provided by SAGAT.

Biomethane price

According to current Italian regulation (della Transizione Ecologica 2022), consumers can obtain the natural gas from the grid and claim its renewable origin by purchasing an equivalent amount of biomethane Guarantees of Origin (GO), with one GO being equal to 1.0 MWh. Under this scheme, the price of biomethane to final users is calculated as that of natural gas plus that of the GO.

One of the largest uncertainties surrounding biomethane concerns the price of the GO, as there is no well-developed market for this commodity to date. The Italian national grid manager (GSE: gse.it) regulates the existent market but uncertainties exist in moving beyond 2030.

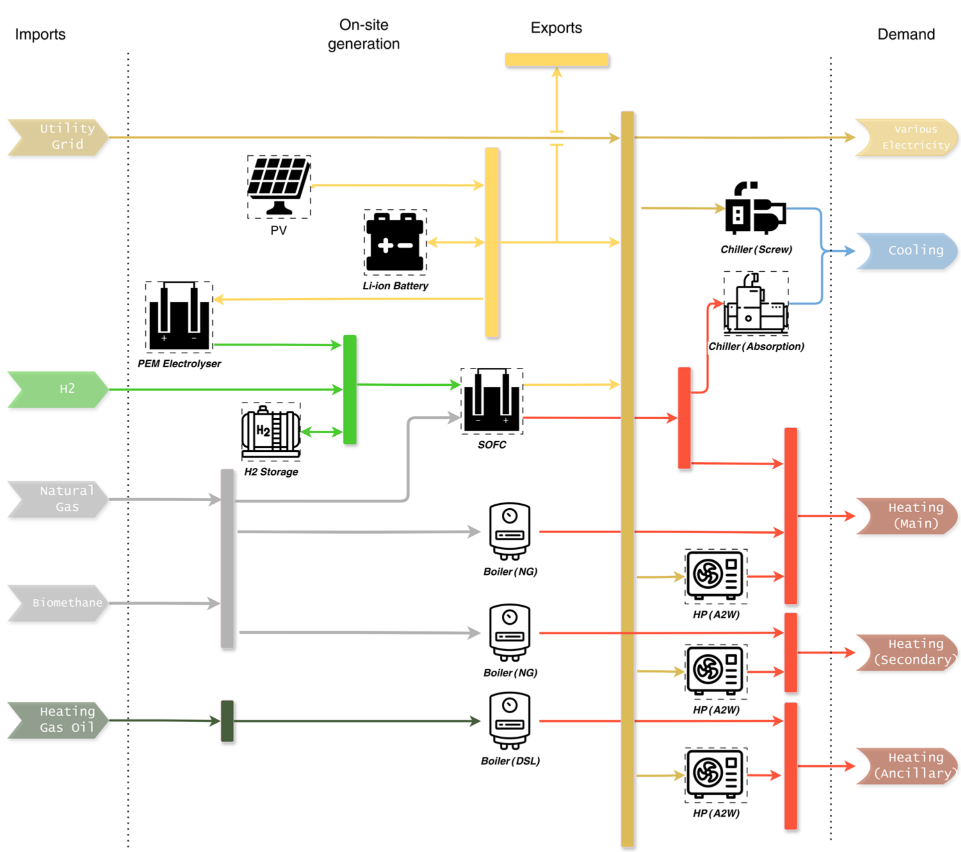


Fig. 3 Representation of the reference energy system of Turin Airport in OSeMOSYS

With the aim to design coherent scenarios addressing this price aspect, it was assumed that biomethane price will be determined by the willingness of heavy industries to pay for the GO. This method relies on the assumption that these industries will be the major uptakers of biomethane, driving demand, and, therefore, price. As heavy industries, like steel-making and cement, are subjected to the Emission Trading Scheme (ETS), the Willingness-to-Pay (WTP) to reduce their carbon footprint is connected to the carbon price. Therefore, in this work the price of a biomethane GO was estimated as the amount that an entity subjected to the ETS scheme would need to pay to purchase emissions allowances (EUA) corresponding to the use of an equivalent amount of fossil natural gas. This can be calculated as the price of the tonne of carbon dioxide multiplied by the emission factor of natural gas, as described by the equation below:

$$WTP_{GO} = Carbon\ Price\ [euro/t_{CO2}] \cdot Emission\ Factor_{NG}\ [g_{CO2}/kWh]/1000$$

The carbon price itself is subjected to potential future volatility. Although several works attempted to project carbon price development in the following decades (CRU 2024; Hintermayer 2020; Strefler et al. 2021; Zaklan et al. 2021; Faure et al. 2024; Enerdata 2030; Quemin 2022; Pietzcker et al. 2021; Abrell et al. 2024; Holz et al. 2021; Intergovernmental Panel on Climate Change 2022), the results suggest an increasing verge, especially after 2040.

In order to account for this variability, three carbon market-GO price scenarios have been designed, as shown in Fig. 4. The low and high scenarios represent the envelop of the price trajectories retrieved from the above-mentioned literature studies, whereas the mean scenario is the average of the low and high trajectories.

Biomethane emission factor

The Airport Council International (ACI) developed the guidelines to support airports in accounting their emissions: the Airport Carbon Accreditation (ACA) manual (Airport Council International 2020): the guide leaves to airports the choice to consider lifecycle emissions for biomass-based fuels. When it comes to biomethane, this is a crucial point as large variability for its emission factor exists, depending on the feedstock and the production pathway.

Figure 5 shows the distribution of lifecycle emission factors of biomethane, as resulting from selected literature sources. The values range from 150 gCO_{2e}/MJ to negative values of up to -100 gCO_{2e}/MJ. The negative GHG emissions for biomethane production pathways are related to the used of manure as feedstock: the negative figures are related to the contribution of the carbon credits, defined to account for the avoided methane emissions, in the counterfactual scenario (i.e. manure left on the ground).

In order to capture the full variability of biomethane lifecycle emission factors, three scenarios have been designed:

- a typical scenario, corresponding to the most frequent value found in literature;
- a zero scenario, representative of a case in which lifecycle emissions are not accounted;
- and a typical negative scenario, in which a typical, negative value for biomethane produced from manure was considered.

Hydrogen supply

Once fuel cell technologies are considered, a major source of uncertainties is related to the real availability of a supply of—green—hydrogen. This will depend on the future evolution of national and international energy system, and the role of hydrogen in it, as well as on the deployment of local infrastructures.

It is out of the remit for this work to evaluate the various hydrogen value-chains that could supply the airport site, this topic which has been addressed by many other studies (Alexandrou 2022; Amose 1998; Mintz et al. 2006). To address this issue, two scenarios have been considered in

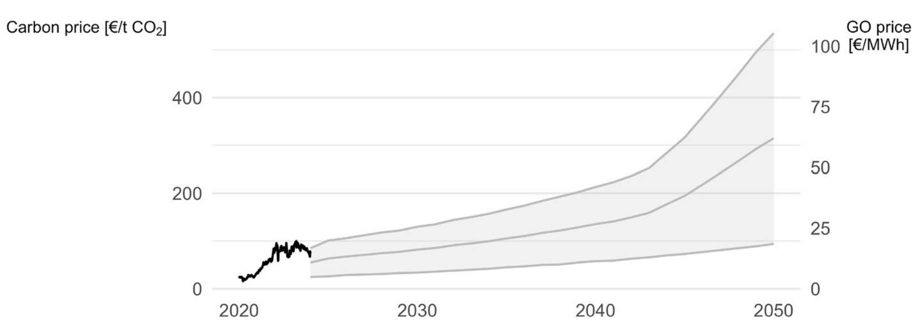


Fig. 4 Scenario assumptions on the development of carbon price (left axis) and related price of biomethane (right axis). Carbon price range was chosen by enveloping the trajectories derived from literature. Three scenarios (low, mean, and high) were then selected. The price of a GO was calculated as the carbon price multiplied by the emissions avoided by replacing natural gas with zero-emission biomethane, representing the WTP of uptakers

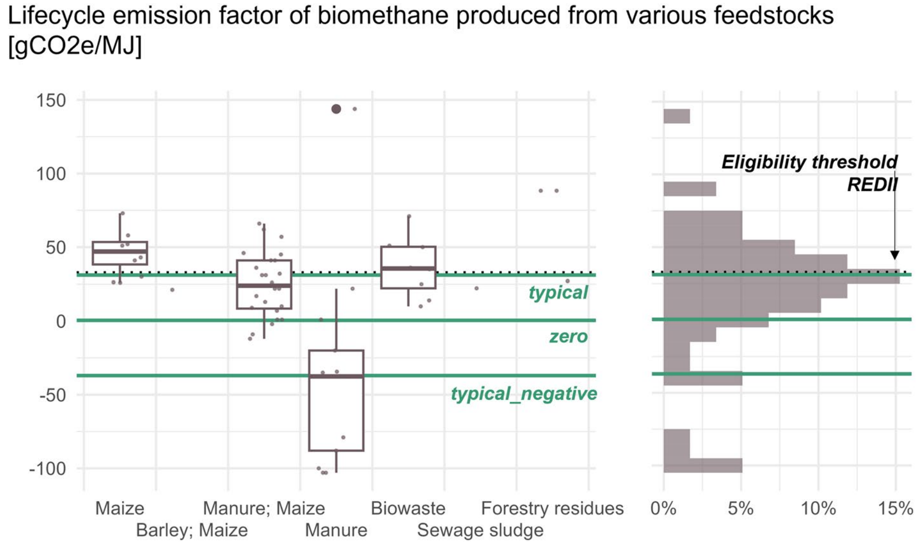


Fig. 5 Variability of lifecycle emission factor for biomethane and scenario assumptions. The emission factors are derived from (et al. 2020; Parliament and Council 2018; Prussi et al. 2020). Three scenarios were selected: the typical scenario in correspondence of the most frequent emission factor according to literature sources; the zero scenario, corresponding to a zero-emission factor biomethane; and a typical negative scenario, corresponding to values characteristic of manure-derived biomethane

this analysis: one with and one without an external hydrogen supply. In the scenario featuring the external hydrogen supply, this was assumed to be available only after 2040, as no plans are currently in place to develop local infrastructure in the airport area.

The projection of green hydrogen price in the long term is even more challenging than for biomethane, as the market is at an infant stage of deployment. Production price of green hydrogen are currently assessed in the range of 3 and 7 €/kg (Parkinson et al. 2018). These figures are expected to drop dramatically in future decades, close or even lower than 1 €/kg (International Energy Agency 2022; International Renewable Energy Agency 2021), mainly driven by the reduction in the cost of electrolysers and a larger availability of renewable energy capacity. To this, hydrogen delivery costs, which depending on the transport volume and mode can make up a significant share of the cost of this commodity (Alexandrou 2022), should be added.

For the purpose of this study, a baseline scenario characterised by a low-price range of 2 €/kg (approximately 70 €/MWh) has been chosen. However, in order to account for future uncertainties, a mean and high price scenarios, respectively, at 4 and 6 €/kg, were considered by a sensitivity study.

It could be argued that, as observed for biomethane, hydrogen demand (and related price) may be led by heavy industries. On the other hand, the scale-up of the production capacity for hydrogen has less theoretical constrains than biomethane's, and it could become cheaper in a future with a power system mostly based on renewable production.

Concerning the emission factor of hydrogen produced via electrolysis, this significantly varies depending on the technology, electricity source, and transportation route (Shaya and Glöser-Chahoud 2024; Kolb et al. 2022; Puig-Samper et al. 2024). However, when hydrogen is produced from renewable electricity, its environmental impact is generally low (Puig-Samper et al. 2024; Sinha and Brophy 2021; Prussi et al. 2020). In this study, it was considered that the airport will purchase only green hydrogen produced from renewable electricity, and that the hydrogen supply will only be available in 2040, in a highly decarbonised environment. Therefore, a lifecycle emission factor of zero has been attributed to the hydrogen used at the airport.

Examined scenarios

The various scenarios designed to capture the variability in biomethane price, emission factors, and availability of hydrogen supply were merged, as shown in Fig. 6, in order to study their possible interactions. As concerns the external hydrogen supply, all the simulations considered a low-price

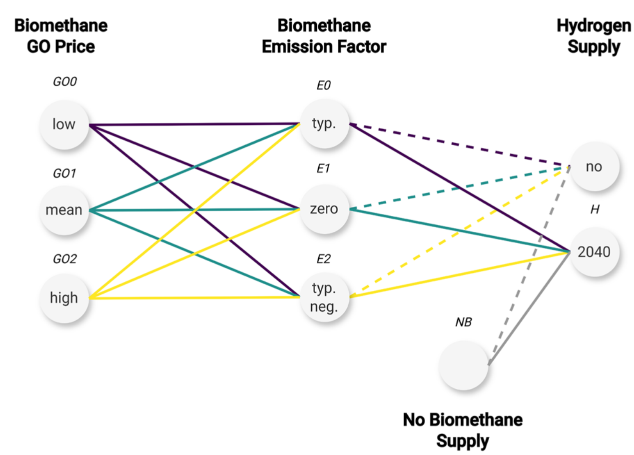


Fig. 6 Combinations of scenarios for biomethane GO price, biomethane emission factor, and hydrogen supply availability used to generate optimal development pathways. The labels in italics report the respective scenario code

scenario, whereas the mean and high ones were used in the second stage of the analysis.

This exercise resulted in 18 alternative scenarios and as many optimal energy system development pathways. The scenarios are identified by means of their respective scenario codes. In addition to this set, two cases were considered, in which no biomethane is available in future decades. The two scenarios differ on the availability of the external hydrogen supply. This was done in order to compare the evolution of the airport energy system, with and without biomethane.

In all the scenarios, a decarbonisation trajectory was imposed to Torino Airport's energy system, setting a 55% reduction target by 2030 and an ultimate 97% reduction target in 2050. The 3% residual emissions was left to avoid over-constraining the optimisation model. The small residual amount in 2050 is not found to affect the overall configuration of the system, and it may be easily covered by external carbon off-settings.

Results and discussion

This section presents the results of the modelling, focusing on the configuration of the optimal development for the energy system, under the different scenario. First, the scenarios without the availability of biomethane (NB and NBH) are presented, as benchmark. Following that, the impact of the introduction of biomethane in the airport energy supply is investigated, considering different price levels and emission factors. The analysis considers the two end-uses of biomethane, i.e. the fuel cell and space heating, evaluating how different development strategies can affect the configuration of the system and the overall consumption of biomethane.

Scenarios without biomethane

The benchmark scenarios without biomethane are consistent with previous studies on airport and large-infrastructure decarbonisation, which identify electrification of heating and extensive deployment of on-site renewable electricity generation as unavoidable measures in the absence of low-carbon gaseous fuels.

Figure 7 shows the annual energy balance for electricity and main heating in the scenarios without biomethane use.

When neither biomethane nor hydrogen supplies are available (NB), no fuel cell capacity is installed at the airport. This happens for two reasons, one technical and one economical. On the one side, on-site hydrogen production is constrained by the limited areas suitable for PV installation, so that only small fuel cell sizes could be technically sustained. On the other side, sustaining the entire fuel cell blend solely through on-site hydrogen production is considered uneconomical by the model, due to the low power-to-power efficiency of this storage solution. In this case, the decarbonisation pathway is mostly based on the installation of PV capacity and electrification of heating.

When hydrogen supply is available (NBH), it becomes economically sustainable to provide a clean blend to a small-size fuel cell (0.25 MW_e), after 2040. However, the size of the fuel cell is limited by the intermediate decarbonisation targets, as the necessity to feed it with natural gas in the medium term would lead to higher emission levels than the

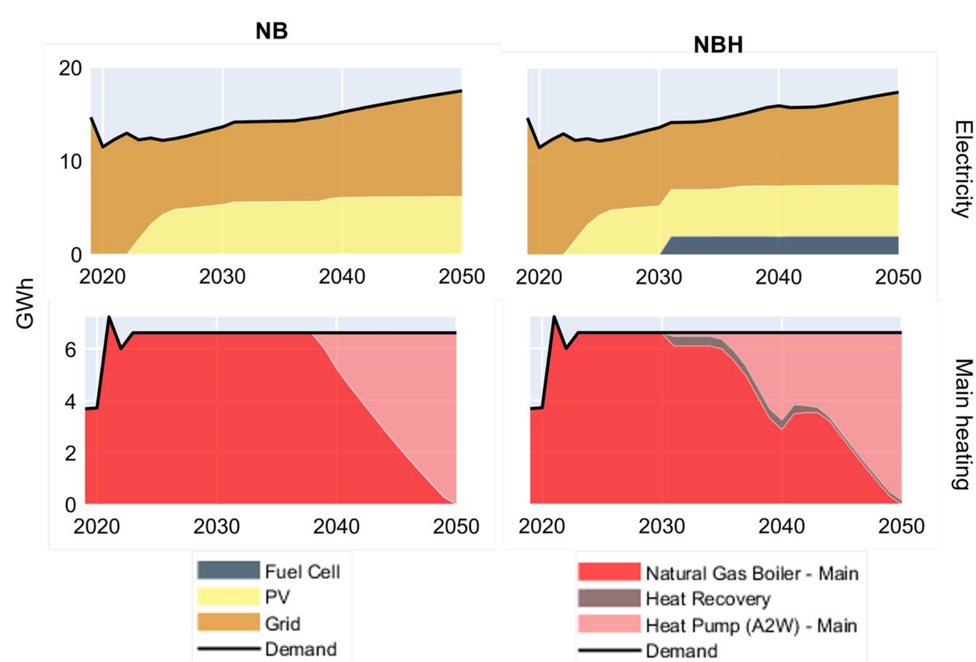


Fig. 7 Annual energy balance for electricity (top) and main heating (bottom) for scenarios without the availability of biomethane supply. NB: neither biomethane supply nor hydrogen supply; NBH, no biomethane supply, hydrogen supply from 2040

imposed trajectory. Also in this scenario, the installation of PV capacity remains pivotal for the decarbonisation strategy.

In both scenarios, it clearly emerged that electrification is a needed measure to achieve the decarbonisation targets, since no alternative exists to fully greening the heating sector. In the NBH scenario, electrification comes into play earlier, as the installation of the fuel cell lowers the price of electricity, but also because of the need to offset the additional emissions generated by the fuel cell, as it is initially fed by fossil natural gas. As a confirmation, when a green hydrogen supply becomes available, the rate of electrification slows down and aligns to that of the NB scenario. The fuel cell only partly contributes to the heating demand, because of the small size and the low thermal efficiency.

The electrification of heating reaches nearly 100% in both scenarios, at 2050. Excluding the increase in airport activities (e.g. increased passengers traffic), the contribution of electrification of heating increases the electricity demand of about 20%, with respect to the airport's 2019 consumption. This additional consumption is mostly covered by grid electricity, accounting for 65% and 57% of the provision in 2050 for the NB and NBH scenarios, respectively.

Similar modelling efforts applied to airports and other energy-intensive facilities report that gas-based technologies become incompatible with deep decarbonisation targets unless supplied with near-zero-carbon fuels. In this respect, the results obtained here confirm the robustness of electrification-driven pathways as a reference solution against which alternative strategies, such as biomethane integration, can be assessed.

Scenarios with biomethane

Figure 8 shows the installed fuel cell capacity in 2040 and 2050, under different scenarios. The maximum fuel cell size varies significantly across the different scenarios, ranging from 0.25 MWe up to 1.0 MWe. The main enabler of a fuel cell-based strategy appears to be the availability of GO at an affordable price. In particular, fuel cell capacity ranges from 0.50 MWe to 1.0 MWe in the low-price scenario. Conversely, the mean and high price of GO tend to limit the size of the fuel cell, which, in most cases, is bound between 0.25 MWe and 0.50 MWe.

In presence of an external hydrogen supply from 2040, a larger fuel cell size is installed. Generally, the gap between the scenarios with and without the hydrogen supply is 0.25 MWe. In some instances, additional fuel cell capacity is added after 2040 to exploit the availability of low-cost hydrogen, although this is not a constant in the observed scenarios.

In the typical emission factor scenario, the fuel cell size is generally capped at 0.50 MWe, also in the case of an external hydrogen supply. In the zero and negative scenarios, no major differences are observed for the medium and high price cases, but for the low price the size of the fuel cell is significantly higher. This suggests that GO price is an influent determinant for the installation of the fuel cell. However, it also shows that considering positive lifecycle emissions for biomethane would limit the maximum size of the fuel cell, because it would not satisfy the stringent emissions reduction required in the 2040–2050 period. Moreover, it can be observed that, also in the case of an external supply of green hydrogen, the size of the fuel cell is still capped for the low-price scenario, indicating that lifecycle emissions from biomethane would become unsustainable also before 2040.

As described, another potential end-use of biomethane at Torino Airport is the space heating sector. The combustion of biomethane in conventional natural gas boilers is a decarbonisation measure in competition with the electrification of the heating sector though heat pumps. It is hence interesting to understand under which conditions biomethane results more competitive than heat pumps and vice versa.

Figure 9 shows the rate of electrification of the heating sector, expressed as share of the total heating demand covered by heat pumps. Generally speaking, significant electrification rates are only observed after 2040. As observed for the fuel cell size, the main variable affecting electrification rate is biomethane price. Under a low-price scenario,

Fig. 8 Installed fuel cell capacity under different scenarios. Each box represents an emission scenario. Dark bars show installed fuel cell capacity in 2040, light bars that in 2050

biomethane is more competitive than electrification so that when no or negative emission factors are considered for biomethane, no heat pumps are installed. This is notwithstanding the fact that increased self-generation of electricity at the airport site decreases the operating costs of heat pumps. In fact, when typical emission factors are considered for biomethane, only a portion of heating demand can be satisfied through conventional boilers.

In the medium price scenario, strong electrification of the heating sector is shown, towards 2050. However, when negative biomethane emissions are considered, a mix of electrification and conventional gas boilers results more competitive. This, as will be later explained in details, is due to the fact that the generation of negative emissions from the purchase of biomethane would enable the airport to keep on using shares of fossil natural gas in the mix. This reduces the operating costs of gas boilers with respect to the sole use of biomethane.

In all the high price scenario, electrification results always more competitive than conventional gas boilers fuelled with biomethane.

The presence of a hydrogen supply does not have major effects on the electrification of heating. The only observed difference regards the low-price scenario in the case of typical emission factors. In this case, the availability of an external hydrogen supply reduces the need of relying on biomethane for the greening of the fuel cell blend, so that more biomethane can be diverted to the heating services, without exceeding the imposed carbon budget.

The different end-use configurations described above lead to different uptakes of biomethane: Figure 10 compares the total biomethane imports for three modelled periods (2019–2030, 2031–2040, and 2041–2050). It can be noticed that biomethane use is negligible or very limited before 2030. In this first period, emissions reduction targets are primarily achieved through decarbonisation of the electricity grid and installation of new PV capacity. The latter measure allows the airport to reduce its environmental footprint while benefitting from the self-production of energy.

Biomethane becomes an integrated part of the energy system only after 2030, in conjunction with the installation of fuel cell capacity and the need to decarbonise the heating sector. The use of biomethane is therefore strongly linked to the fuel cell capacity and, as such, is relevant in all the low-price scenarios. Biomethane results more competitive than on-site hydrogen production to green the fuel cell blend in these scenarios, confirming its importance in the medium term. In the medium and high price scenarios, the smaller

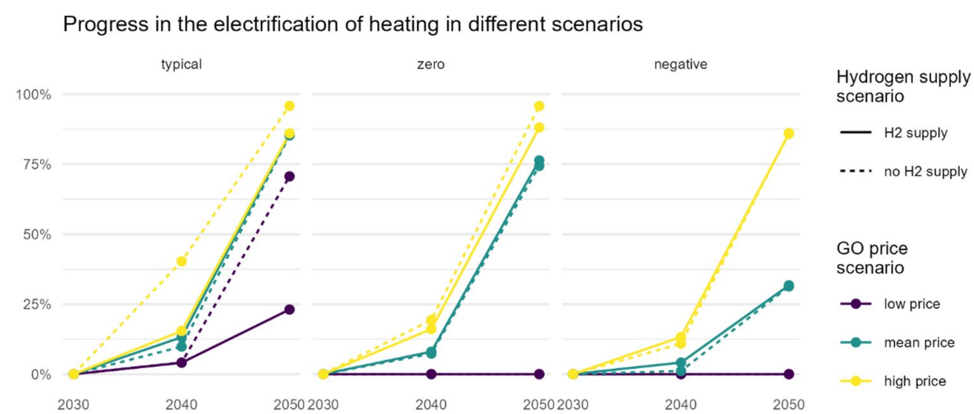


Fig. 9 Share of electrified heating demand at Turin Airport. Each box represents an emission factor scenario, line colour the biomethane GO price, and line type the availability of hydrogen supply. N.B., the share of heating demand only considers the heating sector presently served by natural gas boilers

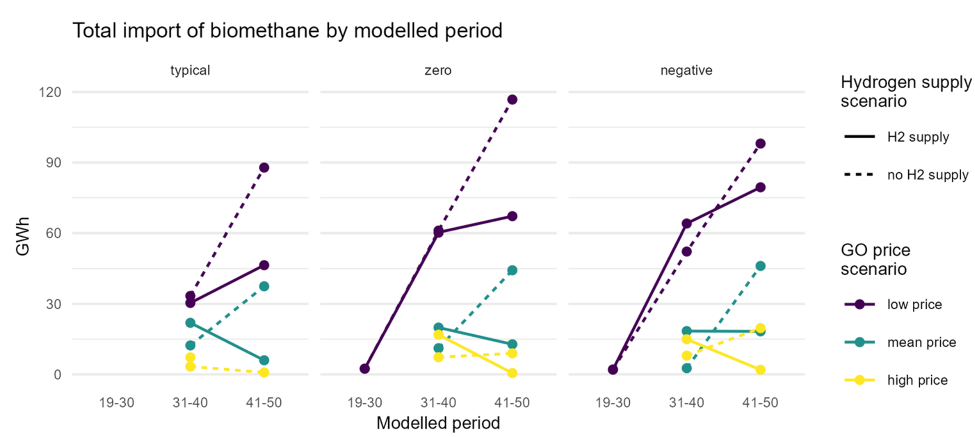


Fig. 10 Total import of biomethane at Turin Airport for the three decades. Each box represents an emission factor scenario, line colour the biomethane GO price, and line type the availability of hydrogen supply

fuel cell size reduces the demand of biomethane. However, the purchase of biomethane still results more convenient than on-site hydrogen production, so that the consumption of biomethane remains proportional to the fuel cell size. In these scenarios, the import of biomethane is always lower than 25 GWh, over the 2031–2040 period.

In the 2041–2050 period, the trend in biomethane consumption diverges for the scenarios with and without hydrogen supply. For high and medium price scenarios, a drop in biomethane consumption is observed when hydrogen becomes available, as the blend of the fuel cell switches to hydrogen and the heating sector is electrified. For the high price scenario, the consumption of biomethane remains almost stable or drops when no hydrogen supply is available, except when negative emissions are considered. Conversely, in the medium price scenario biomethane still plays a role in the 2041–2050 period, as the heating sector gets electrified. For the low-price scenario, biomethane still plays a major role in the 2041–2050 period. This is because, although competitive hydrogen supply is available, biomethane can represent a convenient mean to decarbonise the heating sector. In these case, biomethane consumption over the decade ranges between 45 and 120 GWh.

The influence of the emission factor over biomethane use is worth to be discussed. Considering positive lifecycle emissions for biomethane makes this energy carrier incompatible with long-term net-zero objectives. However, given the low emission factor, this can be considered a valid alternative to replace natural gas in the medium term, but also in the last decade of the modelled period. However, in the way towards the 2050 objective, strong electrification measures and replacement with green hydrogen are required.

When negative emission factors are considered, a counter-intuitive trend is observed. For instance, in the low-price scenario, although the fuel cell size and electrification rate are similar for the zero and negative factors, the consumption of biomethane is smaller for the negative case. This is because accounting for negative emissions allows to offset emissions from natural gas consumption. As a result, it is still possible to achieve net-zero target in 2050 while keep relying on fossil fuels.

Beyond the specific case of Torino Airport, these results highlight the transitional nature of biomethane in local energy systems. Biomethane does not replace electrification as a long-term decarbonisation strategy, but rather acts as a flexibility option that can temporarily sustain gas-based assets when economic and environmental conditions are favourable. The strong sensitivity of optimal system configurations to biomethane GO price and lifecycle emission assumptions suggests that policy-driven market design, rather than purely technical feasibility, will ultimately determine the role of biomethane in demand-side decarbonisation strategies.

Uncertainties assessment

As some limitations are necessarily present in the analysis, a specific assessment have been carried out. In particular, uncertainties are addressed through discrete scenario assumptions rather than probabilistic approaches, and biomethane and hydrogen prices are treated as exogenous inputs. While these choices are consistent with the exploratory nature of the study, they may affect the absolute magnitude of the results and should be considered when interpreting the findings.

This last stage of the analysis aimed to assess the robustness of different strategies to future uncertainties. To this goal, two representative development pathways were selected and the additional economic and environmental costs for the airport quantified accordingly. In particular, the cumulative operational expenditures (OPEX) and emissions of the airport were investigated.

The chosen system configurations were the *GO0E1H* and *GO1E1H*. The *GO0E1H* depicts a strategy largely relying on biomethane, both to fed a large-size fuel cell—0.75 MWe before 2040 and 1.0 MWe after—and to replace natural gas used by boilers for space heating. Specifically, no space heating electrification is envisaged in this configuration. In the *GO1E1H*, instead, the fuel cell size is limited to 0.5 MWe and, after 2040, it heavily relies on external hydrogen supplies. Moreover, electrification is very pronounced, covering more than 75% of the demand in 2050.

Figure 11 reports the cumulative OPEX since 2030 for the two system configurations and varying biomethane and for various hydrogen price scenarios. As it could be expected, the *GO0E1H* configuration, while presenting comparable OPEX to the *GO1E1H* one in low-price scenario, is more susceptible to the variability of biomethane and hydrogen markets. In 2050, the additional OPEX associated with this configuration amount to 14% of the total, in case of mean biomethane and hydrogen price, and to 35% in case of high price scenarios.

Conversely, the *GO1E1H* configuration, which relies on a combination of a smaller fuel cell, grid electricity, and electrification of heating, appears more robust to changes in biomethane and hydrogen market. In 2050, the additional OPEX amount to 7% in case of mean biomethane and hydrogen price, and to 14% in case of high price scenarios.

Figure 12 reports the cumulative emissions of the airport for the two system configurations. The emissions are accounted for the three different biomethane emission factor scenarios and in the absence of biomethane and hydrogen supplies. In these latter cases, it was assumed that the fuel cell would be fed by fossil natural gas.

It can be observed that the consideration of different biomethane emission factors has a non-negligible but overall small effect on the cumulative emissions of the airport.

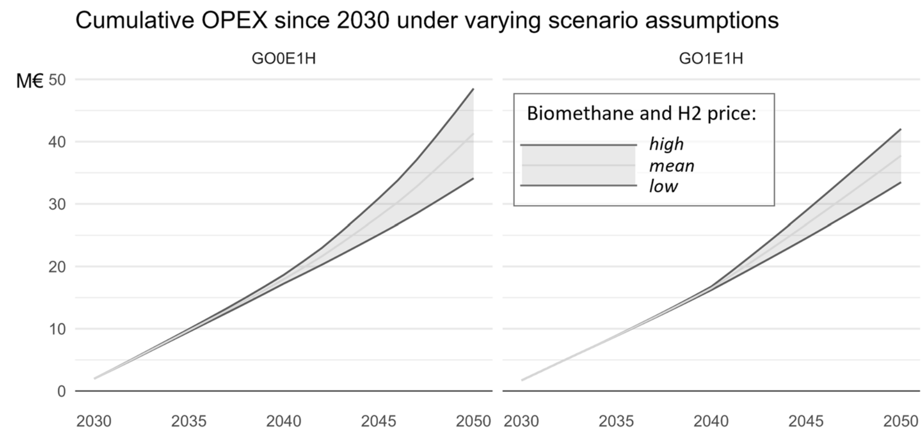


Fig. 11 Impact of hydrogen and biomethane price on the cumulative operational expenditures of selected development strategies

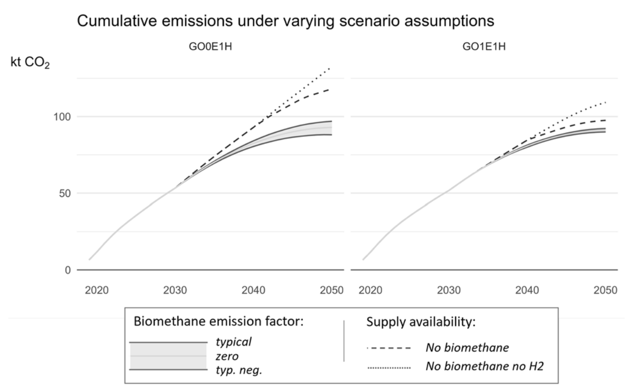


Fig. 12 Impact of biomethane emission factor and availability of external supplies on the cumulative emissions of selected airport development strategies

In 2050, these range between about 87 and 100 kt CO_{2e} for the *GO0E1H* configuration, and between 90 and 92 kt CO_{2e} for the *GO1E1H*.

A larger impact is observed for those scenarios simulating the absence of external biomethane and hydrogen supplies. In the case in which biomethane supply is not available, the cumulative emissions of the airport in 2050 could reach nearly 120 and 100 kt CO_2, respectively, for the *GO0E1H* and *GO1E1H* configurations. If the expectation about a hydrogen external supply are not met, emissions would further rise to 130 and 110 kt CO_2. In this latter scenario, the airport would therefore release, respectively, 1.5 times and 1.2 times more CO_{2e} than what expected, when considering supplies of zero-emission hydrogen and biomethane.

Additionally, a perspective that could further strengthen the role of biomethane concerns the integration of power-to-gas (PtG) upgrading routes. Several studies (e.g. (Bensmann et al. 2014)) indicate that combining conventional anaerobic digestion with hydrogen-based methanation can significantly increase biomethane yields by converting the biogenic CO_2 fraction into additional methane. In such configurations, the effective biomethane output per unit of feedstock can increase substantially, potentially approaching a doubling of methane production under favourable conditions. From a system perspective, the deployment of PtG biomethane would mitigate one of the key limitations identified in this study, namely the constrained availability of sustainable feedstock. By coupling biomethane production with surplus renewable electricity and green hydrogen, PtG routes could increase the overall availability of renewable methane without proportionally increasing biomass demand. In the context of airport energy systems, this could translate into higher feasible shares of biomethane in both fuel cell operation and heating services, thereby extending the time window during which biomethane can act as an effective transitional fuel. Although PtG biomethane production was not explicitly modelled in this work, its inclusion in future analyses could further reinforce the conclusions regarding the strategic value of biomethane, particularly in scenarios characterised by high renewable electricity penetration and limited hydrogen infrastructure at the demand site.

Conclusion

Biomethane is expected to play a crucial role in the European strategy to reduce the reliance on fossil fuels imports and to decarbonise the energy sector. However, the success of European and national policies is directly linked to the deployment of a robust market for biomethane. Several large energy consumers (e.g. cement and steel-making industries) which need to significantly decarbonise their activities could find an appealing solution in biomethane, potentially leading to changes in the current price dynamics. For this reason, these major uncertainties, related to price and the availability of biomethane, complicate the design of strategies based on this alternative energy vector.

In this work, we investigated the potential role of biomethane in contributing to the transition pathway of the Torino

Airport, where fuel cell-based cogeneration and space heating offer potential end-uses. The uncertainties related to biomethane market were addressed by means of a sensitivity analysis, designing wide-range energy price scenarios. Additionally, the impact different biomethane emission factors and the availability of an external hydrogen supply, after 2040, were factored in.

The results show that biomethane is a key enabler of a decarbonisation strategy, based on the fuel cell energy convertors. Conversely, assuming low or negligible biomethane

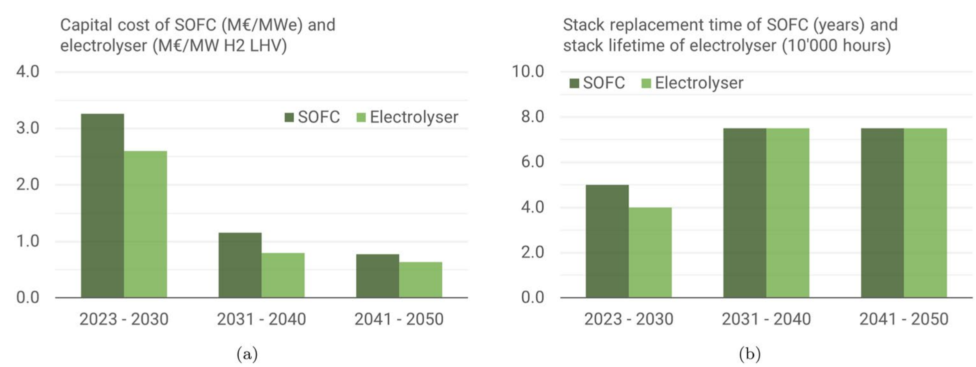
Table 1 Summary of technological parameters. N.B., all data refer to 2019. OEM: Original Equipment Manufacturer; GSE: Ground Support Equipment

CCHP				Installed-capacity(2019)		Sources
SOFC		Natural Gas	Hydrogen	-		OEM Gandiglio et al. (2024); Marocco et al. (2022); Gandiglio et al. (2024)
	Unit size [kW]	250				
	Electric efficiency	0.62	0.65			
	Thermal efficiency	0.20	0.10			
	Total efficiency	0.82	0.75			
	Flue gas temperature [^{circ}C]	320	167			
	Flue gas flow rate [kg/h]	1404	1780			
	Modulation range	50-100%				
	Utilisation factor [h/year]	8000				
Absorption Chiller	Type	Single-stage		-		
	COP [kWc/kWt]	0.7				OEM
Heat Exchanger	Heat losses	5%		-		
PV						
	Efficiency	Capacity Factor	Yield [GWh/MWp]			
Rooftop	22.7%	13.5%	1.18	-		Modelled
Ground-mounted	18.0%	15.6%	1.36	-		Modelled
Storage and Hydrogen production						
Battery	Type	0.25C Li-Ion battery		-		OEM
	Roundtrip efficiency	90%				
	Depth of discharge	20%				
	Power-to-energy ratio	25%	kW/kWh			
Electrolyser	Type	PEM		-		OEM International Energy Agency (2015)
	Efficiency	0.625	MWH2 (LHV)/MWel			
	Operating pressure	30	bar			
Hydrogen vessel	Pressure	300 bar		-		OEM Elberry et al. (2021)
Heating and Cooling						
	Energy source	Thermal efficiency	COP			
Boiler (Main)	Natural gas	0.924		8.8	*MWt*	
Boiler (Secondary)	Natural gas	0.922		1.4	*MWt*	SAGAT
Boiler (Ancillary)	Diesel oil	0.916		2.9	*MWt*	
Screw chiller	Electricity		5.02	7.9	*MWc*	
A2W Heat Pumps	Electricity		2.58	-		OEM
Lighting						
	Illuminance [lm/W]	Utilisation factor				
Conventional bulbs	62.6	62%		0.81	*MWe*	Morgan Pattison et al. (2017)
LED bulbs	133	60%		0.22	*MWe*	
Vehicles						
	Fuel economy					
Diesel cars	40.4	kWh/100 km				Centre. (2020)
Electric cars	12.7	kWh/100 km				
Diesel GSE	10 - 84	kWh/mi				Heathrow Airport Limited (2013)
Electric GSE	2.5 - 23	kWh/mi		-		

Table 2 Summary of economic parameters. N.B., all data refer to 2019. OEM: Original Equipment Manufacturer. [1] Include annualised costs for stack replacement

Technology price							Sources
		Capital cost	Operating cost		Lifetime		
		M€	M€ y-1	*per*			
CCHP		7.62	0.34	*MWe*	20	*years*	
	SOFC	5.94	0.191	*MWe*	20	*years*	OEM
	fuel cell	3.26					
	other	2.68					
	stack replacement	0.95		*MWe*	5	*years*	
	System and Design	1.68	0.15	*MWe*	20	*years*	
PV							
	Rooftop	1.44	0.018	*MW*	25	*years*	OEMIRENA (2022)
	Ground-mounted	1.01	0.018	*MW*	25	*years*	
Storage and Hydrogen production							
	Battery	0.48		*MWh*	15	*years*	OEM
	Electrolyser	2.6	0.13	*MWH2 (LHV)*	40’000	*hours*	International Energy Agency (2015, 2022); Thema et al. (2019)
	Hydrogen vessel	0.08		*MWh*	20	*years*	International Energy Agency (2015); Houchins et al. (2022)
Heating and cooling							
	A2W Heat Pumps	0.227	0.006	*MWt*	20	*years*	Marshall and Duquette (2022); Department for Business, Energy & Industrial Strategy (2019)

Fig. 13 Capital cost scenarios for the SOFC and electrolyser. Scenarios for stack replacement time of SOFC and stack lifetime of electrolyser



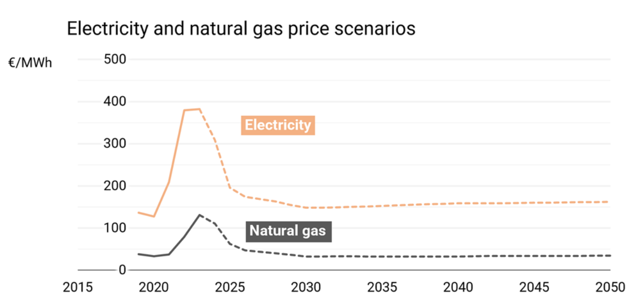


Fig. 14 Electricity and natural gas price scenarios. Solid lines indicate historical data, dashed lines are projections

availability, the model does not provide fuel cell capacity installed at the airport, as feeding it only by hydrogen produced on-site resulted uneconomical.

The price of biomethane is the major determinant of the problem, in particular with respect to the definition of the fuel cell optimal size. Under the low-price scenario, fuel cell ranges from 0.50 to 1.0 MWe (providing about 30% and 60% of electricity consumption, respectively), whereas under higher price scenarios it is generally limited below 0.50 MWe. The role of biomethane is fundamental to provide a green blend to the fuel cell in the medium term; meanwhile, hydrogen production/supply is gradually scaled-up. This positive dynamic explains the key role of biomethane as transitional fuel.

Replacing natural gas with biomethane in boilers, for heating services, results more convenient than direct

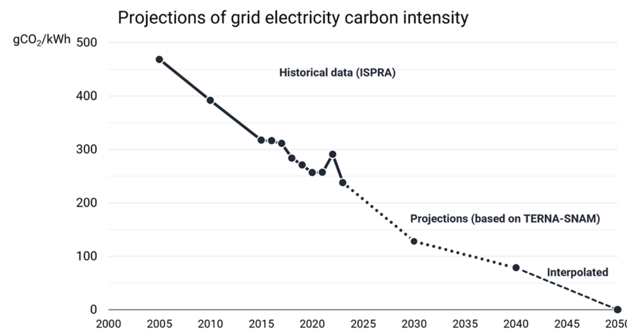


Fig. 15 Scenario considered for the carbon intensity of electricity grid

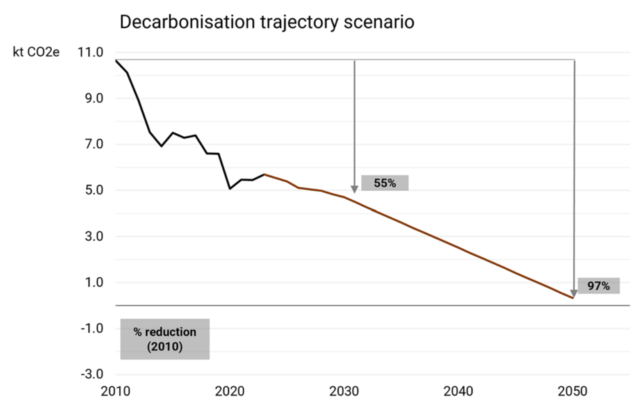


Fig. 16 Decarbonisation trajectory imposed to the model

electrification, under the low-price scenarios. However, as the price increases, the diversification of heat sources, or even the total electrification of heating, resulted a preferable option.

As the final goal of the exercise is to curb airport operations emissions, the carbon intensity of biomethane production (expressed in gCO_{2e}/MJ) is an important point for the analysis. When considering an average emission factor, the biomethane results a non-viable options for achieving the long-term net-zero target. Nonetheless, biomethane remains relevant in the medium term. Conversely, considering negative emission factors favours the uptake of biomethane. At the same time, when negative emission factors for biomethane are considered, the system may keep relying on fossil natural gas consumption, as fossil emissions are off-set by biomethane.

Finally, the analysis of selected system configurations revealed how scenarios reliant on large fuel cell are less resilient to future uncertainties about biomethane and hydrogen supplies. In the worst case, following such strategies could lead to an increase up to 35% of the total operational expenditures, in the period 2030 to 2050. Moreover, the need to rely on fossil natural gas use to cover potential unavailability of biomethane and hydrogen supplies, in the long term, could have disruptive effects on the environmental commitments of the airport, raising cumulative emissions up to 1.5 times, in 2050. Therefore, for strategies based on fuel cells, taking actions to secure these green fuels supplies is pivotal to limit potential drawbacks. Conversely, configurations featuring moderate fuel cells sizes coupled with strong electrification for heating proved to be more robust.

Future research may extend the present analysis in several directions. The modelling framework could be expanded to explicitly represent interactions with the regional or national power system, allowing the assessment of feedback effects between large energy consumers and electricity generation mixes. Additionally, probabilistic approaches could be adopted to complement the scenario-based analysis and better quantify the likelihood of alternative market developments for biomethane and hydrogen. Finally, applying the proposed methodology to multiple airports or other large infrastructures would allow a broader evaluation of the transferability and generality of the findings.

Table 3 Summary of the parameters defining the temporal dimensions of the model. [1] One typical day for each month from March to October, one typical day for winter months. [2] Closing hours of the airport (00:00-5:00) were aggregated in a single time step

Temporal dimension	Parameter	Definition	Value
Investment	Validation years	*Years of known airport operations, used to validate the model*	2019–2023
	Horizon	*Period over which investment decisions are made*	2024–2050
	Investment cycles	*Resolution of the investment decisions*	1 year
Operational	Typical days	*Number of days used to represent a full operational year*	9[1]
	Time step	*Time unit over which dispatch decisions are made*	1 h
	Time slices per day	*Number of time steps per day*	20[2]
	Time slices per year	*Number of time steps per year*	180

Appendix A. Details on energy system model implementation

This appendix reports additional information concerning the implementation of the energy system optimisation model realised for Torino Airport. Attached information includes technical specifications of the technologies included in the model as well as economic assumptions concerning equipment and energy prices and their projected evolution. Moreover, technical details concerning temporal resolution and emissions reduction trajectories are provided.

Table 1 and Table 2, respectively, report the technical specifications of the main technologies included in the model and the main economic assumptions concerning equipment price and technical lifetime.

Figure 13 reports important information concerning the projected price of fuel cells and electrolysers. The projections, which see a sharp decrease in prices right after 2030, were based on the same scenario assumptions employed by the IEA hydrogen roadmap report (International Energy Agency 2015), depicting a future characterised by high deployment of hydrogen-based technologies.

Figure 14 shows the evolution of electricity and natural gas price considered in the study. For the purpose of the analysis, it was assumed that, after the spikes observed after the energy crisis, the price of both electricity and natural gas will gradually recover, eventually reaching pre-crisis levels after 2030. After 2030, a gradual increase in both electricity and natural gas price was imposed, based on the price indices sourced from the FF55 MIX scenarios (European Commission 2020). No decoupling between electricity and natural gas prices was envisaged.

Figure 15 shows the assumed decrease in electricity carbon intensity. For 2030 and 2040, the intensity was derived applying ISPRA's accounting methodology (Caputo 2020) to the energy mix projected by TERNA-SNAM's scenarios for Italy (TERNA and SNAM 2022). For 2050, it was assumed that the grid intensity will reach near-zero values, in agreement with various literature sources (Enerdata 2024; International Energy Agency 2021; International Renewable Energy Agency 2018).

Figure 16 shows the emissions reduction trajectory imposed to the airport model. These see a 55% reduction of emissions in 2030 (with respect to 2010) and to gradually reach net zero in 2050. It is noted that, in 2050, the reduction target was set to 97% rather than 100%, in order not to overconstrain the optimisation model. The 3% residual emissions are considered negligible for the purpose of this analysis.

Key information concerning the temporal representation of the model is reported in Table 3. The modelled period ranges from 2019 to 2050. The first four years are used to calibrate the model(Prussi et al. 2023), whereas the energy system configuration is optimised starting 2024. An operational year of the airport is represented with 9 typical days. The typical days are defined for each spring, summer, and autumn month, whereas one typical day represents the whole winter. The choice of the typical days was made heuristically and verified using the indicators developed by Poncelet et al. (Poncelet et al. 2024). The temporal resolution of the operation decisions is one hour, aligned to the literature on local investment planning models (Cuisinier et al. 2021). Closing hours of the airport were aggregated in a single time step, as the energy demand is relatively stable in those hours and no intermittent renewable generation is present.

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Author Contributions L.L. and M.P. substantially contributed to the design of the work and creation of the software model. L.L. and M.P., with the support of M.N. and D.A.M, performed the analysis. L.L. drafted the first version of the document, further refined by M.P. D.A.M. supported in the creation of the model on the software, used in the work. D.C. approved the version to be published, and he supervised the research activity planning and execution. D.C. was also responsible for the funds acquisition. M.O. and G.R. provided core data for the analysis and verified the model results. M.O. and G.R. also provided useful insight to improve the model.

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Data Availability No datasets were generated or analysed during the current study.

Declarations

Conflict of interest The authors declare no conflict of interest.

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