Energy for Sustainable Development 73 (2023) 205–217

Contents lists available at ScienceDirect

Energy for Sustainable Development

journal homepage: www.journals.elsevier.com/energy-for-sustainable-development

Assessing environmental benefits of the transition from standard fossil fuels to liquefied natural gas: The Sardinia Region case study

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A R T I C L E I N F O

Keywords:
Liquefied natural gas
Environmental benefits
Emission factors
Energy forecasting
Fossil fuel transition

A B S T R A C T

The ever-increasing attention to environmental pollution and the greenhouse effect, together with the need to reduce harmful emissions into the atmosphere, has led to a general enforcement of stricter legislation worldwide which imposes the adoption of more efficient and sustainable solutions in many different fields. The use of traditional fossil fuels must be reduced, favoring both renewable energy sources and alternative fuels. This paper outlines a procedure for calculating the environmental advantages of using liquified natural gas (LNG) instead of traditional fossil fuels in terms of reduced emissions: it is based on the choice and application of emission factors (EFs), available through a dedicated and extensive database managed and updated by the European Environmental Agency (EEA). Whenever the EF database lacks data, additional literature studies and databases are used to integrate the missing information. The proposed methodology is then applied to the Sardinia Region: starting from data regarding regional energy needs, the emissions deriving from the current situation are calculated to define a reference point to be compared with two forecast scenarios. These assume that, over a 10-year horizon, certain shares of fossil fuels will be substituted by LNG. Comparisons are made between the emission levels of six different compounds ($PM_{2.5}$, PM_{10}, CO, CO_2, NO_X, SO_X) showing that, overall, LNG adoption can be considered effective in reducing air pollution for the compounds considered. In particular, as an example, reductions of up to 70 % of PMs and 38 % of CO_2 can be achieved for the thermoelectric sector, whereas for the transportation sector the reductions of the same compounds can be respectively 15 % and 10 %.

Introduction and state of the art

Natural gas (NG) is a fossil fuel commonly present in underground reservoirs, alone or together with coal or petroleum. It is composed of a variety of hydrocarbons (mostly methane, but also heavier molecules like ethane, pentane, and others) and is one of the strongest options for replacing other petroleum derivatives in the medium-term future, because it has a cleaner combustion with respect to traditional fossil fuels (Kumar et al., 2011). Natural Gas can be employed in several different fields: from energy generation (residential and large-scale thermoelectric plants) to industrial processes as well as fuel for both marine and terrestrial transport.

NG has been highlighted as a transition energy source towards decarbonization in recent years, notably in the liquid form of LNG. Indeed, NG has lower emission factors than coal and oil, helping to reduce Greenhouse Gas (GHG) emissions and facilitating a sustainable approach to development. Moreover, NG can be considered a suitable energy vector towards the adoption of hydrogen-based technologies (Bedani et al., Nov. 2020). Hence it can open the way to hydrogen and new sustainable fuels in various fields of use, from the heavy land transport sector to that of maritime bunkering.

When considering the pollution reduction targets established by the new European regulations, liquefied natural gas (LNG) is fundamental in a range of fields (e.g., from the industrial to the transportation and residential sectors). The EU Project "SIGNAL", funded within the framework of the Interreg Maritime Italy-France Programme, supports and incentivizes the use of LNG-based technologies on islands and in border regions where the connection to the main continental natural gas (NG) distribution network is difficult.

In the following, a brief review of the worldwide state of the art about LNG applications will be carried out, in order to underline the importance of developing such studies and justify the EU Interreg Programme approach.

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https://doi.org/10.1016/j.esd.2023.01.008
Received 22 February 2022; Received in revised form 7 December 2022; Accepted 10 January 2023

General studies

Ayaburi et al. (2021) described natural gas development focusing on LNG projects and related policies in Africa, showing that the degrees of development are extremely varied: as examples, Egypt has a prominent LNG infrastructure. In its ESP (Emerging Senegal Plan), Senegal emphasizes the need for expanding projects about LNG and oil in order to develop an energy market which is competitive and lower electricity prices. Ghana has put measures in place to use LNG for electricity production, while in Nigeria, because of its poor LNG transport infrastructure, a large part of the gas produced is flared (NASA, 2022). The authors argue that a precise projection of energy consumption is required since it will allow emerging countries to manage their natural gas allocations in a more efficient way.

In their 2020 study on future use of biomethane in the UK, Richards and Zaili (2020) analyze the current situation and future trends, saying that LNG (in addition to other sources) will become increasingly important to satisfy UK demand.

Thermoelectric sector

Considering thermoelectric production, Jaramillo et al. (2007) carried out a study to assess the life-cycle emission levels for greenhouse gas (GHG), sulfur oxides (SO_x), and nitrogen oxides (NO_x) for electricity production. The fuels compared are NG, LNG, synthetic natural gas (SNG), and coal. When current technologies are taken into account, the authors discovered that coal has a greater influence on environmental emissions than a mixture of commercial NG, LNG, and SNG. Nonetheless, all of the fuels investigated (a mix of domestic SNG, LNG, NG and coal) have virtually the same life-cycle greenhouse gas emissions when carbon capture and sequestration (CCS) technologies are used. Moreover, the study points out that, for SO_x and NO_x, it is necessary to account for emissions that happen in the initial phases (i.e., extraction, treatment, and transport) of the NG life cycle.

Manych and Jakob (2021) studied the situation of the Philippines, a country whose electricity demand is rapidly growing and that, for a variety of social and economic reasons, as well as a lack of viable options for baseload, is intended to be met primarily by coal. Nevertheless, excluding untapped geothermal sources ("often not viable due to economic or technical constraints") and public resistance to nuclear power due to frequent earthquakes, in its 2017–2040 energy agenda the Department of Energy planned the use of LNG and the construction of a gas hub facility in order to increase grid stability and avoid power outages.

Another paper, proposed by Hardisty et al. (2012), studied the GHG emissions for a conventional open cycle gas turbine (OCGT) compared to a sub-critical plant fed by black coal. The study found that, using standard LNG in an OCGT cycle produces about 38 % less GHG emissions per MWh of electricity produced during its entire life cycle. The paper points out that the implementation of more modern and efficient technologies (i.e., ultra-supercritical cycles) helps to reduce the emission levels of coal powered plants.

Energy recovery and conversion

The regasification process can be exploited to recover part of the cold exergy, as Messineo and Panno (2011) suggested. Their paper proposes coupling an LNG regasification facility to a network of liquid CO_2, feeding cold to various sites. The feasibility of this system is assessed and analyzed by the authors when this technology is applied to an agronomical food production area in Sicily. The results show that the food production efficiency rises, while conservation and transformation costs are lowered, also bringing economic and environmental benefits to the local area.

Regasification cold exergy can be recovered also according to Oshima et al. (1978), who investigate the possibility of producing liquid hydrogen. The authors propose a small-scale model to demonstrate the feasibility of a regasification plant that can provide liquid hydrogen (LH_2) and LNG. The generator is paired with a cryogenic-type Stirling Engine, operating between gases (LH_2 or LNG) and ambient temperatures. The full scale of the proposed power station is 1000 MW.

Dispenza et al. (2009) and Dispenza et al. (2009) studied the possibility of coupling a combined heat and power (CHP) plant with an LNG stream in cryogenic conditions. The first paper estimates the modular units' regasification capacity ($2 \cdot 10^9$ SMC/year), while the authors assess the feasibility of the proposed plant structure using a thermodynamic and economic analysis in the second paper.

Transport sector

The adoption of LNG-based technologies can also be adopted in the transport sector, as Arteconi and Polonara (2013) proposed in a recent study. The authors analyzed the positive and negative aspects when LNG is used as vehicle fuel. The paper considered the suitability of in-situ liquefaction, as well as comparing different gas supply options with respect to Italy. The results show that the purchase of LNG is convenient for terminals that are up to 2000 km from the central distribution and regasification hub. Moreover, in-situ liquefaction requires specific technologies with high process efficiency and low gas price. Jiao et al. (2020) took Guangzhou (China) as a case-study city in order to create a quantitative analytical model about the co-benefits of reducing CO_2 and air pollutant emissions: the authors discovered that promoting LNG in the transportation sector (for example, vehicles and ships) requires the use of air pollutant end removal systems and HPDI (high-pressure direct injection) gas engines.

When LNG is used as a fuel for vehicles, heavy-duty engines are more suitable to be fed with this particular fuel. Unfortunately, the results of the research activity in this field point in different directions. Cordiner et al. (2008) proposed a study, both experimental and numerical, about combustion and exhaust emissions of dual fuel (DF) engines fed with diesel and NG. Cheenkachorn et al. (2013) studied the effects of feeding an engine with a mix of LNG and diesel on both performance and emissions. The authors ran tests to investigate the power, the specific fuel consumption, the torque, the thermal efficiency, the volume efficiency, the NO_x, total hydrocarbon, CO and CO_2 emissions, finding that the dual fuel operation showed less thermal and volumetric efficiency and less specific fuel consumption. Furthermore, when an engine is fueled with an LNG and diesel mix, carbon monoxide and total hydrocarbon emissions are increased, while CO_2 and NO_X emissions are reduced. Recent research activities investigated the impact of DF operating mode on pollutant emissions, engine performance and combustion parameters on a standard diesel engine. The authors' research found that, at medium and high loads, it is possible to obtain a reduction of soot and NO_X while lowering the brake-specific fuel consumption (BSFC) (Lounici et al., 2014), and a comprehensive review on the topic can be found in Chen et al. (2018). However, DF operation at low loads produces an increase in unburned hydrocarbons and carbon monoxide emissions (Lounici et al., 2014). Different research groups pointed out that adding hydrogen to the dual fuel mix (NG and diesel) of a natural gas engine can help to increase thermal efficiency while reducing CO, HC and particulate matter (PM) emissions, while considerably increasing NO_X emissions, a subject covered by a review by Chen et al. (2019), and also investigated in 2016 by Karagöz et al. (2016). Wei and Geng (2016) found that DF greatly reduces CO_2, PM and NO_X emissions, while there could be an increase of HC and CO emissions. Smajla et al. (2019) carried out a wider analysis, also considering the economic and ecological benefits connected to changing from diesel to LNG as a heavy-duty vehicle fuel. Their research found that LNG use shows a higher cost-effectiveness if compared to standard fuels as well as a reduction in CO_2 emissions.

LNG can also be used as a substitute for standard fossil fuels in the maritime transport sector. Lim and Choi (2020) analyzed the possibility of coupling an Organic Rankin Cycle (ORC) aboard NG powered ships, exploiting the cold exergy recovery from LNG regasification as thermal sink. Elkafas et al. (2021) proposed a numerical study of economic and ecological benefits of a case study ship equipped with a DF engine, showing that it is possible to reduce CO_2, NO_X, SO_X, PM and CO by about 20 %, 85 %, 98 %, 99 %, and 55 % respectively, while achieving economic benefits and energy efficiency. Laviola et al. (2018) proposed to generate electrical energy by means of generators, fueled by LNG, installed aboard a floating vessel, to develop a cold ironing infrastructure inside the port of Genoa, with the aim of lowering emissions from moored ships. The paper analyzes the main technical features of the solution proposed giving insights on dimensions of the proposed floating vessels, notable features of the generators, also considering average load factor, fuel consumption and economical aspects.

Transport is a key aspect to fully analyze air pollution emission sources, and assessment of the environmental impacts is fundamental to completely grasp the issue. For instance, given the limitations imposed by the European Union on carbon dioxide emission, it is necessary to monitor real vehicle fuel consumption (FC) using onboard FC monitors (OBFCM) and onboard diagnostic (OBD) devices. Pavlovic et al. (2021) examined the accuracy of OBFCM and OBD for both light and heavy-duty vehicles, finding that acceleration, average vehicle speed, and total trip characteristics all affect accuracy. The authors proved that fuel consumption and distance measures acquired for longer periods (full voyages) show higher accuracy and precision compared to shorter trips.

Aims of this study

The various papers analyzed above show how NG, and in particular LNG, has characteristics that make it a key element in defining strategies for sustainable energy management. The adoption of LNG based solutions, thanks to the possibility of exergy recovery during the regasification process and the cleaner combustion process, can help reduce energy consumption, while allowing reduction of CO_2 and other compound emissions in different fields of applications. Furthermore, thanks to the limited level of technology required, LNG can potentially be used in any area of the planet, without substantial constraints relating to the development of the country or to the availability of qualified technical skills.

In this sense, for a more effective employment and dissemination of this strategic resource for decarbonization, it is important to determine a methodology useful to calculate the pollutant emission reduction achievable through LNG-based technologies. A correct assessment and evaluation of the benefits is, in fact, an essential tool for decision makers and all stakeholders in defining coherent strategies towards sustainability. For that purpose, in this paper an analysis is described aimed at evaluating the environmental benefits that a transition to liquefied natural gas (LNG) could achieve for areas that are not currently served by gas networks, in particular islands, and therefore use high impact fossil fuels. In this sense, LNG is identified as a transition energy carrier, capable of facilitating the adoption of hydrogen in the medium term and immediately achieving significant benefits in terms of reducing emissions of GHG and pollutants, such as SO_X and fine dust. The case study of the Italian island region of Sardinia is presented: this island does not currently have a natural gas network, so other fossil fuels such as fuel oil, diesel propane-air mixture and even coal are widely used. This situation is common to many islands or isolated regions of the planet, which can therefore immediately benefit from the use of LNG to largely replace the high-environmental-impact fuels currently used. Starting from final energy demand data (2019) of the region, it is possible to elaborate the environmental benefits considering two different forecast scenarios, each with a 10-year horizon (2030). Each scenario hypothesizes the substitution of a certain share of standard fossil fuels in favor of LNG. Different sectors (tertiary, industrial, residential, and marine transport) are analyzed, dedicating extra care to thermoelectric production and terrestrial transport sectors.

The novelty of the present study lies in the application of the proposed methodology to the Sardinia Region, which historically has always had a peculiar energy network configuration. The study presents how the introduction of an LNG based infrastructure can be useful to reduce the environmental pressure, especially for specific pollutants. The methodology developed can be easily replicated and applied to other regions with similar characteristics in order to properly evaluate a transition towards more sustainable fuels and technologies.

Methodology for the assessment of emission reduction

To estimate the environmental benefits deriving from the substitution of shares of fossil fuels with LNG, the authors propose a methodology which is discussed in the following part of this paper.

Fuel mix and final energy consumption data

The most important step is to correctly collect the information that defines the fuel mix and the relative energy share representing the final energy consumption data. In this analysis, that information is referred to the Sardinia Region: Fig. 1 summarizes the data gathered, the reference year is 2019 (Franci et al., 2020).

These data are usually collected, processed, and stored by public authorities (government or local authorities), energy distributors and managers, research institutes, and others. The data are necessary to give an estimate of the present-day situation, when it is necessary to profile the energy needs of specific sectors. In this analysis the sectors investigated are residential, tertiary, industrial, transport (terrestrial and marine), and large-scale thermoelectric production. Thus, the present-day scenario in terms of emission levels is well described: in this way it is possible to define a necessary benchmark against which to establish comparisons.

Selection of emission factors

The identification of emission factors is another key step for the correct application of the proposed methodology. Generally, emission factors are necessary to estimate the amount of a certain substance introduced in the environment subsequentially to a certain activity or process.

The choice of emission factors must be made with great care, since they are very specific and depend on the fuel considered, process (e.g., combustion or industrial process), technology (e.g., a gas turbine or a boiler) and other secondary factors.

The more detailed the scale of the analysis is, the more it is possible to be specific in the selection of the emission factors. When a wide-scale analysis (like the one adopted in this work) is used, it is necessary to consider some general assumptions, to summarize and group the necessary information. This explains why such a detailed approach must be considered case by case, and in this specific application it was not feasible. For these reasons, the emission-factor coefficients adopted in the present assessment are selected from those reported by the “EMEP/EEA (2019)”.

This document is paired with a rich and ample database, which contains emission factors for different sectors, processes, fuels, and technologies.

Depending on the level of precision requested in the emission factor selection procedure, the database is organized to differentiate between different emission factor tiers. Each tier level (called TIER 1, TIER 2, TIER 3) increases the specificity and the detail level of the respective emission factors.

Considering the scale of the proposed case study analysis, this work focuses on selecting emission factors among the TIER 1 category. This implies that, for each sector considered, it is necessary to consider some typical abatement system technology, since it is not possible to differentiate each pollution source singularly. Whenever this differentiation is

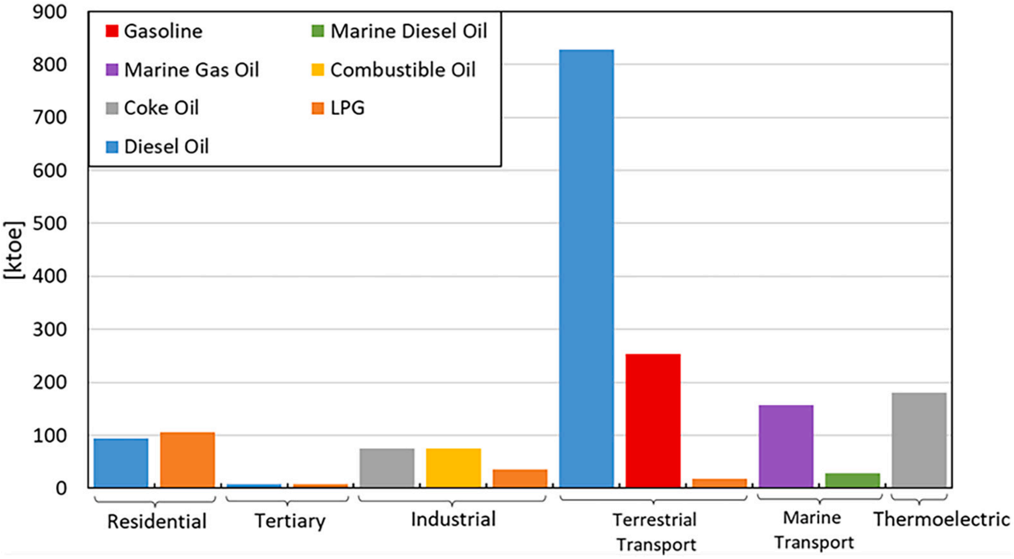


Fig. 1. Final energy consumption for the Sardinia Region for the year 2019 (Franci et al., 2020).

feasible, i.e., in case of a building scale analysis, TIER 2 and TIER 3 emission factors should be chosen.

Focusing on the TIER 1 approach, the EMEP/EEA database groups fuels into macro-categories, based on the thermo-physical properties of each fuel. The grouping criterion is presented in Table 1.

As previously mentioned, whenever the EMEP/EEA database lacks data, they are integrated using secondary sources. In the case of carbon dioxide, a national database is used to retrieve the missing information (ISPRA, 2019).

The analysis of the marine sector requires integration with external sources to gather data about the emission factors for carbon dioxide: the 2014 International Maritime Organization Directive (IMO, 2014) indicates the values to be used as reference when calculating emissions from fossil-fuel-powered ships. Moreover, dedicated literature was consulted to gather complete information on emission factors for LNG-fed vessels (Alanen et al., 2020), using a slightly different approach. In fact, according to the approach proposed by Alanen et al. (2020), the emission factors for each compound are determined as a fraction of the corresponding value when traditional fossil fuels are considered (Alanen et al., 2020).

Focusing on carbon monoxide emissions for LNG-powered ships, the emissions for this pollutant are not calculated in this work. This can be explained considering that the emissions of CO are heavily dependent on the combustion process efficiency. In fact, modern engines are designed to function with minimal fuel consumption and polluting emissions, thanks to dedicated components for injection, ignition, and control systems that are specific for the fuel they were designed to be fed. The conversion, to lower the environmental impact with different fuels, does not always meet the optimization criteria for all parameters considered.

Table 1
Fuel categories for the calculation of TIER 1 emission factors - EMEP/EEA Handbook (EMEP/EEA, 2019).

TIER 1 fuel type	Associated fuel types
Hard coal	Coking coal, other bituminous coal, sub-bituminous coal, coke, manufactured “patent” fuel
Brown coal	Lignite, oil shale, manufactured “patent” fuel, peat
Gaseous fuels	Natural gas, natural gas liquids, liquefied petroleum gas, refinery gas, gas works gas, blast furnace gas
Heavy fuel oil	Residual fuel oil, refinery feedstock petroleum coke, Orimulsion, bitumen
Light oil	Gas oil, kerosene, naphtha, shale oil
Biomass	Wood, charcoal, vegetable (agricultural) waste

Appendix A lists all the emission factors considered during the calculations, with reference to the specific sector and pollutant. The table also shows the source from which each coefficient was drawn.

Present-day benchmark emission calculation

For comparison purposes, it is necessary to calculate a benchmark value for each pollutant emission. This allows one to assess the environmental benefits between the present-day benchmark emission levels and the proposed scenario calculated values.

The total annual mass for each compound analyzed is given by Eq. (1):

$$M_{pollutant,year} = C_{energy,year} \bullet EF_{pollutant} \tag{1}$$

where:

- $M_{pollutant,\ year}$ is the amount of compound emitted into the atmosphere yearly [t] or [Gt];
- $C_{energy,\ year}$ is the total amount of energy provided by the considered fuel [GJ] or [kWh];
- $EF_{pollutant}$ is the specific emission factor for the sector, activity and fuel under analysis [g/GJ] or [kg/GJ].

In some cases, it is possible to find the emission factor coefficient reported as a mass ratio (e.g., kg/t_{fuel}): thus, it is necessary to consider the fuel specific Lower Heating Value (LHV) to calculate the total amount of energy $C_{energy,\ year}$.

Table 2 shows the LHVs for each fuel considered in the environmental benefit analysis.

As an example, it is possible to illustrate the necessary calculations made for the two sectors analyzed (residential and tertiary). The results are reported in Table 3.

Table 2
Lower heating value for each fuel analyzed.

Fuel	LHV	UM
Diesel oil	42.6	MJ/kg
Gasoline	43.4	MJ/kg
Petroleum coke	29.5	MJ/kg
Comb oil (gas oil)	42.8	MJ/kg
LPG	45.5	MJ/kg
Marine diesel (MGO-MDO)	42.8	MJ/kg
LNG	48.6	MJ/kg

It is worth noting that “large-scale thermoelectric production” emissions have been analyzed individually, as they bear an importance that can justify a possible conversion of the Sardinian thermoelectric sector without the other areas being involved.

In addition, the “terrestrial transport” sector has also been analyzed individually. This was necessary given the complexity of the sector itself and the need to apply a specific methodology to assess environmental benefits, which will be illustrated separately.

At this point, in Table 4, the calculated global emissions are listed, one by one, for every compound, for the reference year (i.e., 2019) for the case study analyzed (i.e., Sardinia Region).

As mentioned above, the analysis of the thermoelectric sector has been considered separately, and the results are given in Table 5.

The results shown in Tables 4 and 5 are obtained applying the methodology described previously.

Table 4
Calculated Sardinia Region total emissions 2019.

Compound	Specific total emissions, 2019	UM
$PM_{2.5}$	330	t
PM_{10}	374	t
NO_x	15,525	t
SO_x	5659	t
CO	1603	t
CO_2	3400	Gt

Table 5
Calculated total annual emissions, thermoelectric sector.

Compound	Specific total emissions, 2019	UM
$PM_{2.5}$	148	t
PM_{10}	193	t
NO_x	1090	t
SO_x	3793	t
CO	38	t
CO_2	1600	Gt

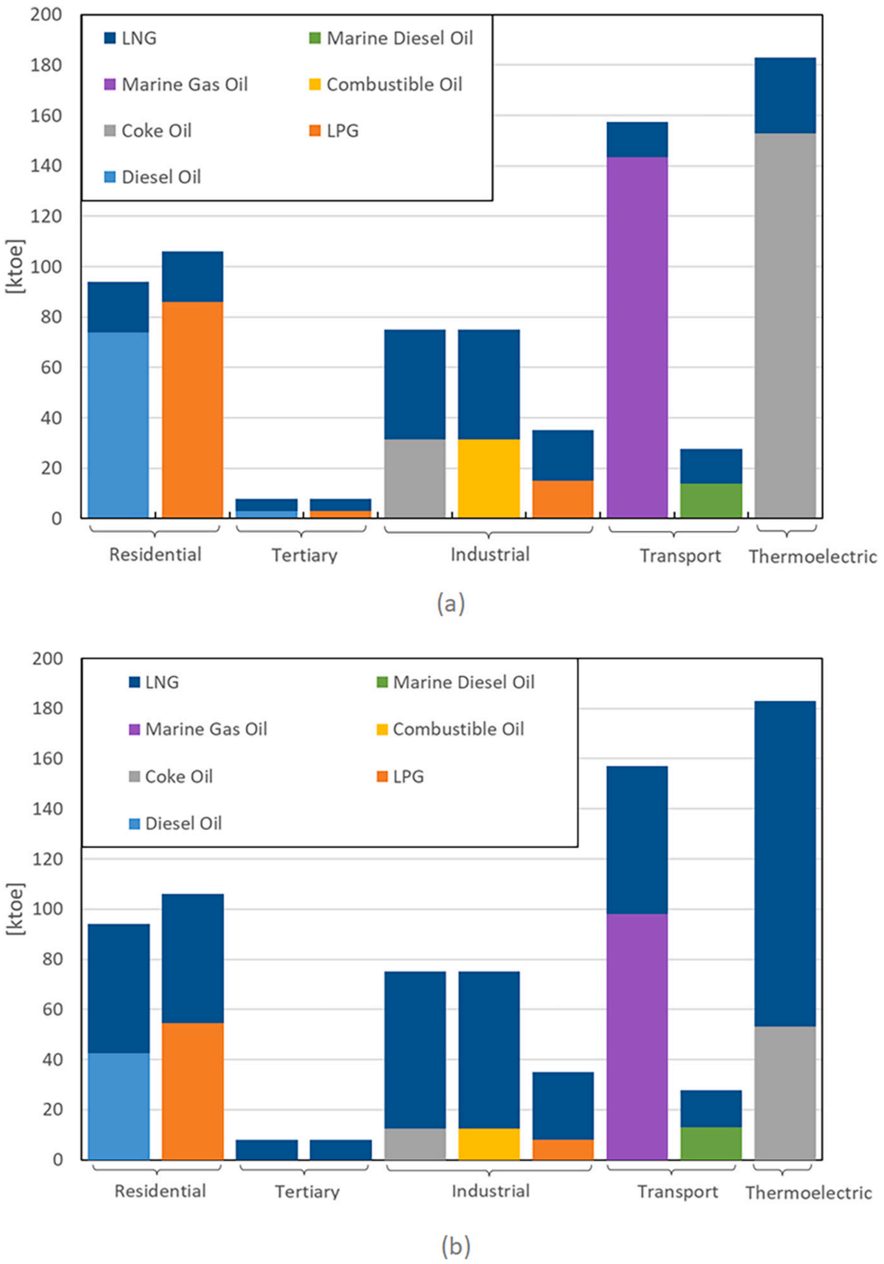
Proposed future scenario emission calculation

The application of Eq. (1) allows us to calculate the emissions for the proposed forecast scenarios. The calculations are made considering different quantities of fuels that contribute to satisfying the energy demand for the Sardinia Region. In particular, the total amount of energy required by each sector will remain the same as the reference year (2019), but different shares of standard fossil fuels are hypothesized to be substituted by a certain amount of LNG. The forecast scenarios share the same 10-year time horizon, but they fundamentally differ for the supporting measures as well as regulatory framework that should be developed during the timespan considered. The scenarios analyzed are defined as “low penetration (LP)” and “high penetration (HP)”, and they are accurately described in Sollai and Fadda (2020). The LP scenario assumes the absence of new support measures for the deployment of LNG and CNG as alternative fuels in road and maritime transport, the failure to adopt new environmental policy measures such as the establishment of a sulfur emission control area (SECA) in the waters of Sardinia, and the maintenance of the relevant regulatory framework introduced by ARERA in 2019 for distribution networks and LNG supply infrastructure, without the implementation of what is envisaged for the methanization of Sardinia in the PNIEC (*Piano Nazionale Integrato per l’Energia e il Clima* 2030 - National Integrated Energy and Climate Plan 2030) guidelines and by the provisions of Article 60 of the Italian “Simplification” Decree-law. The HP scenario is based instead on the introduction of new support measures for the diffusion of LNG and CNG as alternative fuels in road and maritime transport, the implementation of new environmental policy measures such as the establishment of a SECA in the waters of Sardinia, and the implementation of what is provided for the methanization of Sardinia in the guidelines of the PNIEC and the provisions of Article 60 of the Italian “Simplification” Decree-law, with the introduction of regulatory interventions for the infrastructures necessary for methanization that allow for the full integration of the natural gas (transport and distribution) network in Sardinia with the national network, and lastly with the application of the equalization mechanisms in infrastructure costs that are applied in the rest of the country to the transport network and distribution networks.

The emissions avoided are evaluated by direct comparison between the present-day results and the emissions calculated for the proposed scenarios.

Table 3
Calculation example of total annual emissions, residential and tertiary sectors.

			Compound	EF	UM	Emission [t]
Residential						
Diesel oil	3,935,592	GJ	$PM_{2.5}$	1.5	g/GJ	5.9
	1,093,220,000	kWh	PM_{10}	1.5	g/GJ	5.9
			NO_x	69.0	g/GJ	271.6
			SO_x	79.0	g/GJ	310.9
			CO	3.7	g/GJ	14.6
			CO_2	202.9	kg/GJ	$799*10^3$
LPG	4,438,008	GJ	$PM_{2.5}$	1.2	g/GJ	5.3
	1,232,780,000	kWh	PM_{10}	1.2	g/GJ	5.3
			NO_x	51.0	g/GJ	226.3
			SO_x	0.3	g/GJ	1.3
			CO	26.0	g/GJ	115.4
			CO_2	109.0	kg/GJ	$484*10^3$
Tertiary						
Diesel oil	334,944	GJ	$PM_{2.5}$	1.5	g/GJ	0.5
	93,040,000	kWh	PM_{10}	1.5	g/GJ	0.5
			NO_x	69.0	g/GJ	23.1
			SO_x	79.0	g/GJ	26.5
			CO	3.7	g/GJ	1.2
			CO_2	202.9	kg/GJ	$68*10^3$
LPG	334,944	GJ	$PM_{2.5}$	1.2	g/GJ	0.4
	93,040,000	kWh	PM_{10}	1.2	g/GJ	0.4
			NO_x	51.0	g/GJ	17.1
			SO_x	0.3	g/GJ	0.1
			CO	26.0	g/GJ	8.7
			CO_2	109.0	kg/GJ	$37*10^3$



(a)

(b)

Fig. 2. Forecast fuel mix for “low penetration” (a) and “high penetration” scenarios (b), respectively (Franci et al., 2020).

As mentioned above, the starting point is the forecast energy mix that is necessary to completely characterize the future scenarios. For purposes of clarity, Fig. 2 shows the amount of energy required by each sector, considering the different fuels that are necessary to generate it.

At this point, it is possible to calculate the total mass, on an annual basis, for each of the compounds considered. For brevity, an example of the calculation performed is shown in Table 6.

Emission reduction assessment – terrestrial transport

In the mid-term, the assessment of emissions relies on a proper definition of the substitution scenario of old and polluting vehicles with newer ones, which are compliant to more updated and environmentally friendly limits. In this framework, a further development of the share of LNG vehicles must be accounted for since it is influenced by LNG distribution and availability, as well, and the increase of LNG vehicle share can further increase the reduction of emissions of some atmospheric pollutants.

It is possible to define the effective reduction of emissions, induced by transition to LNG, as the difference between the reduction of emissions linked to the physiological replacement of the older part of the vehicle fleet and the further reduction that is due to the fact that a fraction of the new vehicles will be LNG powered. Hence, the calculation is based on a standard estimation of fleet substitution, N_{TOT}, in the presence of a share of LNG powered vehicles, which is definitely larger than the one that would take place in the absence of transition to LNG.

It is possible to use the share of new vehicle registrations in the reference period, N_{TOT}, and to consider that a percentage of them, C, will be powered by LNG, in order to calculate the number of new LNG powered vehicles:

$$N_{LNG} = N_{TOT} \bullet C \qquad (2)$$

where:

Table 6
Calculated annual total emissions, for residential sector, LP (a) and HP (b) scenarios.

			Compound	EF	UM	Emission [t]
(a) Emission calculation example LP scenario						
Diesel oil	3,098,232	GJ	$PM_{2.5}$	1.5	g/GJ	4.6
	860,620,000	kWh	PM_{10}	1.5	g/GJ	4.6
			NO_x	69.0	g/GJ	213.7
			SO_x	79.0	g/GJ	244.7
			CO	3.7	g/GJ	11.4
			CO_2	202.9	kg/GJ	$629{*}10^3$
LPG	3,600,648	GJ	$PM_{2.5}$	1.2	g/GJ	4.3
	1,000,180,000	kWh	PM_{10}	1.2	g/GJ	4.3
			NO_x	51.0	g/GJ	183.6
			SO_x	0.3	g/GJ	1.1
			CO	26.0	g/GJ	93.6
			CO_2	109.0	kg/GJ	$393{*}10^3$
LNG	1,674,720	GJ	$PM_{2.5}$	0.2	g/GJ	0.5
	465,200,000	kWh	PM_{10}	0.2	g/GJ	0.5
			NO_x	42.0	g/GJ	23.1
			SO_x	0.3	g/GJ	26.4
			CO	22.0	g/GJ	36.8
			CO_2	102.1	kg/GJ	$171{*}10^3$
(b) Emission calculation example HP scenario						
Diesel oil	1,779,390	GJ	$PM_{2.5}$	1.5	g/GJ	2.6
	494,275,000	kWh	PM_{10}	1.5	g/GJ	2.6
			NO_x	69.0	g/GJ	122.7
			SO_x	79.0	g/GJ	140.5
			CO	3.7	g/GJ	6.5
			CO_2	202.9	kg/GJ	$361{*}10^3$
LPG	2,281,806	GJ	$PM_{2.5}$	1.2	g/GJ	2.7
	633,835,000	kWh	PM_{10}	1.2	g/GJ	2.7
			NO_x	51.0	g/GJ	116.3
			SO_x	0.3	g/GJ	0.6
			CO	26.0	g/GJ	59.3
			CO_2	109.0	kg/GJ	$249{*}10^3$
LNG	4,312,404	GJ	$PM_{2.5}$	0.2	g/GJ	0.8
	1,197,890,000	kWh	PM_{10}	0.2	g/GJ	0.8
			NO_x	42.0	g/GJ	181.1
			SO_x	0.3	g/GJ	1.3
			CO	22.0	g/GJ	94.9
			CO_2	102.1	kg/GJ	$440{*}10^3$

N_{LNG} = is the number of LNG vehicles registered in the reference time-span;
N_{TOT} = is the number of new vehicles registered in the reference time-span;
C = percentage of LNG vehicles with respect to total registration.

The contribution to the reduction of each individual vehicle, per kilometer, is the difference between the pollutant emissions of a new vehicle, compliant with current legislation, and the emissions of an analogous LNG powered one, per kilometer traveled:

$$\Delta_{v,km,i} = E_{CL,km,i} - E_{LNG,km,i} \tag{3}$$

with:

$\Delta_{v,\ km,\ i}$ = is the emission reduction for the single LNG vehicle, per kilometer traveled for the ith pollutant $\left[\frac{g_{ith}}{km.year}\right]$;
$E_{CL,\ km,\ i}$ = is the emission level for a single vehicle compliant with current legislation, per kilometer traveled for the ith pollutant $\left[\frac{g_{ith}}{km.year}\right]$;
$E_{LNG,\ km,\ i}$ = is the emission level for a single vehicle powered with LNG, per kilometer traveled for the ith pollutant $\left[\frac{g_{ith}}{km.year}\right]$;

The total contribution for the ith pollutant ($E_{tot,\ i}$) is obtained by multiplying the unit contribution by the share of the total kilometers traveled by methane-powered vehicles, purchased as an alternative to Euro VI and VII diesel, which has been considered as the standard emission level, for new vehicles.

The effective emission reduction, for each pollutant *i*, is given by the following equation:

$$E_{tot,i} = N_{LNG} \bullet \Delta_{v,km} \bullet km_{tot} \left[\frac{g_{i^{th}}}{year}\right] \tag{4}$$

To solve this equation, it is necessary to define the total number of kilometers traveled, per year, by the LNG-powered vehicles, according to different realistic scenarios.

There are two concomitant effects that need to be considered when assessing the impact of possible scenarios for replacing part of the circulating vehicle fleet with methane vehicles. On the one hand, one must account for the complex distribution of engine capacity categories of vehicles; on the other hand, it can be observed that the share of new vehicles replacing older ones, year after year, are compliant with the most recent regulations and, therefore, at least EURO VI.

It is expected that there will be a significant contribution to pollutant reduction mainly due to the enforcement of new anti-pollution regulations, as well as the physiological renewal of the circulating vehicle fleet (Clairotte et al., 2020). Only a small percentage of modern vehicles are powered by natural gas, and the emission reduction can be considered the same as the emission difference between a methane-gas-powered and a Euro VI vehicle. EURO VI limits are very strict, and this concretizes in a small emission difference between a Euro VI diesel and a methane powered vehicle. Those two categories are the most representative when air pollution issues are considered.

For example, the combination of lower CO_2 production, per fuel kWh, and the simultaneous lower efficiency of the methane-powered engine, explains why the reduction of CO_2 emissions, for internal combustion engines, is limited to only about 10 %. Moreover, this value is affected by strong uncertainty, related to individual engine performance.

This consideration applies to the production of carbon dioxide per kilometer and, to an even greater extent, to all pollutants. For this reason, average values can be used for a rough estimate provided that one bears in mind that these values can be affected by great uncertainty, sometimes even greater than the value itself (Cheenkachorn et al., 2013; Clairotte et al., 2020; EMEP/EEA, 2019). For these reasons, the actual reduction of pollutant emissions, due to the spread of vehicles powered by methane gas, is not easily assessable.

Focusing on particulate matter emissions, it is necessary to note that, to be compliant with EURO VI standards, modern internal combustion engines are equipped with particulate abatement systems. These devices, while delicate, complex and with considerable maintenance requirements, bring particulate emissions to levels comparable or even lower than those of methane-powered engines.

However, there is evidence that highlights how emissions from methane and EURO VI diesel vehicles are affected by great uncertainty (Delgado & Muncrief, 2015; EMEP/EEA, 2019).

In addition to the previous considerations, which favor the use of LNG-powered engines, it is necessary to account for some issues that penalize the use of methane engines. As for traditional engines, there are similar observations about the magnitude and uncertainty pertaining those limiting factors (Clairotte et al., 2020; Vermeulen, 2019).

Considering NO_x emissions, LGN-powered heavy vehicles are slightly penalized compared to conventional internal combustion engines (Cornelis, 2019).

Finally, one can focus on hydrocarbon and methane emissions. These losses are, for example, frequent during tank loading and unloading operations, or during refueling phases. Given the gaseous nature of methane, it is more easily subject to accidental emission phenomena. This penalizes methane engines severely, up to off balancing the advantages obtained in relation to CO_2 and particulate emissions.

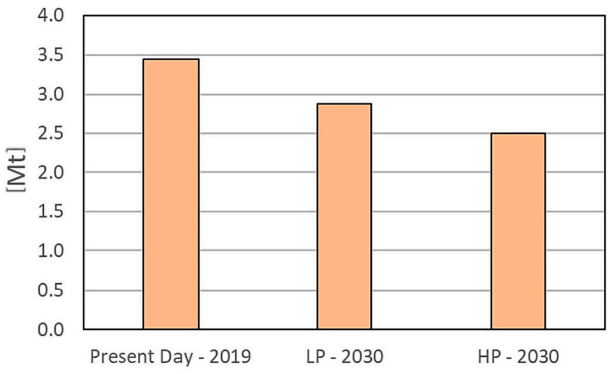


Fig. 4. CO_2 annual emission analysis for the proposed scenarios.

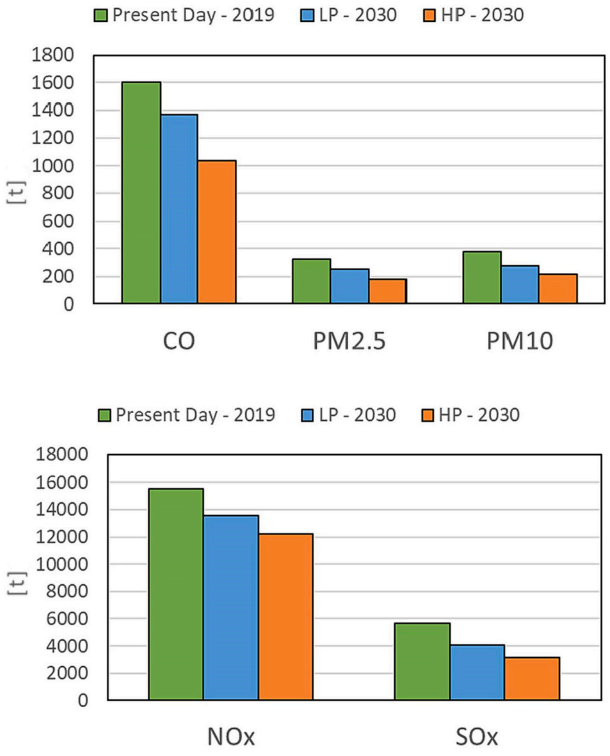


Fig. 3. Total annual emissions (t) broken down into different scenarios.

This topic is covered by an ample and complex literature, which shows a wide dispersion of results. This apparently indicates a controversial issue, but simply highlights the uncertainty of the experimental results.

Results

In the next paragraph, the results of the analysis are presented. The terrestrial transport and thermoelectric production sectors are analyzed separately. Due to discrepancies between the orders of magnitude of the results, the CO_2 emission analysis is reported separately.

Observing the results shown in Figs. 3 and 4, reducing heavy fuel and diesel usage induces a significant diminution in particulate matters (both $PM_{2.5}$ and PM_{10}) and sulfur oxides emissions. A reduction of pollutant emission is forecast for all the compounds considered.

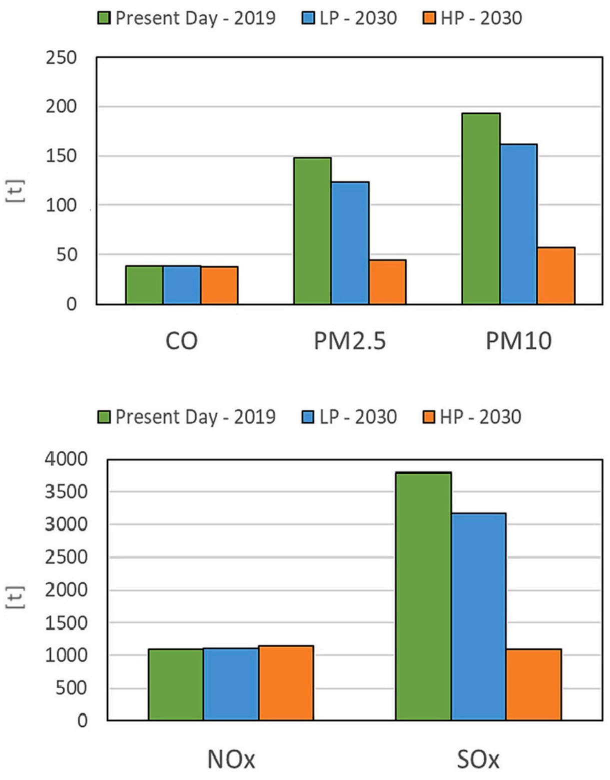


Fig. 5. Total annual emissions (t) broken down into different scenarios – Thermoelectric sector.

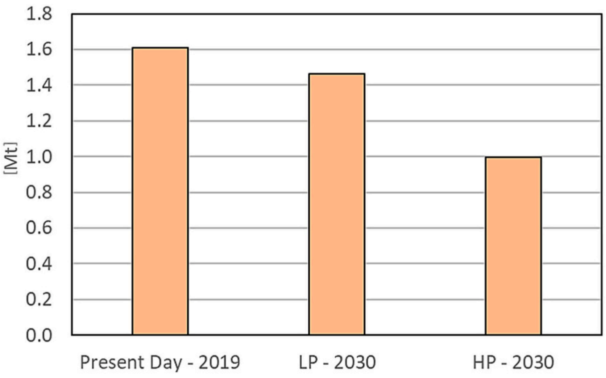


Fig. 6. CO_2 annual emission analysis for the proposed scenarios - Thermoelectric sector.

Environmental analysis results - thermoelectric sector

As explained above, it is useful to analyze the results obtained from the calculation and comparison of emissions levels, for the thermoelectric production sector. The analysis results are reported in Figs. 5 and 6.

As already mentioned, the thermoelectric sector is analyzed separately given its high strategic value. In fact, even though natural gas might not be widely used in the other sectors analyzed, it may be useful to evaluate the conversion of the thermoelectric generation plants of the Sardinia Region. In accordance with the planned regional interventions and, the fuel conversion process is assumed valid only for the Fiumesanto and Sulcis plants, while the Sarroch refinery would continue to power the Sarlux plant.

From the results analysis it can be inferred that, in general, the pollutants whose emission is strongly affected by LNG adoption are particulate matters and sulfur oxides. As for nitrogen oxides, there is a positive variation of 1.3 % with respect to the LP scenario and of 5.5 % in the case of the HP scenario. This is explained considering that the reconverted plants are powered by a single type of fuel (coal). Coal is known for being responsible for high production, during combustion, of particulate matter and sulfur oxides. Table 7 shows the detailed percentage changes for the sector and scenarios considered.

Environmental analysis results - terrestrial transport

To assess the possible effects of the adoption of LNG to cover part of the consumption related to road transport in the Sardinia Region, the following aspects must be considered:

- transport-related consumption is an important source of pollutants (CO_2 and particulate matter, NO_x, VOC, and other substances);
- pollution from vehicular traffic will be subject to a progressive reduction linked to the natural replacement of obsolete vehicles with more modern ones, that are compliant with the anti-pollution regulations (in force or planned), which are increasingly stringent with regard to atmospheric emissions, such as EURO VI and EURO VII (scheduled for 2026);
- reduction of emissions due to the renewal of the circulating fleet can take place naturally or be boosted by incentive and promotion systems.

In this general framework, it should be considered that a share of new the vehicles will be covered by LNG-powered vehicles. This can further bolster the emission of atmospheric pollutants.

To calculate this contribution, it is necessary to define the share of new vehicle registrations planned during the reference period and to consider that a percentage of them will be powered by LNG. In addition, it can be estimated that the contribution to the reduction of each individual vehicle per kilometer is the difference between the emission of vehicle pollutants, compliant with current legislation, and the emission of pollutants from the cars powered by natural gas, per kilometer traveled.

The total contribution is obtained by multiplying the unit contribution by the share of the total kilometers traveled by methane powered vehicles, purchased as an alternative to Euro VI and VII diesel, considering the different scenarios forecast.

As previously discussed and explained in the Emission reduction assessment – terrestrial transport section, the uncertainty affecting the results (in particular for the transportation sector) is of difficult assessment.

There are two concomitant effects that need to be considered when assessing the impact of possible scenarios for replacing part of the circulating vehicle fleet with methane vehicles. On the one hand, one must account for the complex distribution of engine capacity categories of vehicles; on the other hand, it can be observed that the share of new vehicles replacing older ones, year after year, are compliant with the most recent regulations and, therefore, at least EURO VI.

It is expected that there will be a significant contribution to pollutant reduction mainly due to the enforcement of new anti-pollution regulations, as well as the physiological renewal of the circulating vehicle fleet (Clairotte et al., 2020). Only a small percentage of modern vehicles are powered by natural gas, and the emission reduction can be considered the same as the emission difference between a methane-gas-powered and a Euro VI vehicle. EURO VI limits are very strict, and this concretizes in a small emission difference between a Euro VI diesel and a methane powered vehicle. Those two categories are the most representative when air pollution issues are considered.

For example, the combination of lower CO_2 production, per fuel kWh, and the simultaneous lower efficiency of the methane-powered engine, explains why the reduction of CO_2 emissions, for internal combustion engines, is limited to only about 10 %. Moreover, this value is affected by strong uncertainty, related to individual engine performance.

This consideration applies to the production of carbon dioxide per kilometer and, to an even greater extent, to all pollutants. For this reason, average values can be used for a rough estimate provided that one bears in mind that these values can be affected by great uncertainty, sometimes even greater than the value itself (Cheenkachorn et al., 2013; Clairotte et al., 2020; EMEP/EEA, 2019).

Focusing on particulate-matter emissions, it is necessary to note that, to be compliant with EURO VI standards, modern internal combustion engines are equipped with particulate abatement systems. These devices, while delicate, complex and with considerable maintenance requirements, bring particulate emissions to levels comparable or even lower than those of methane-powered engines.

However, there is evidence that highlights how emissions from methane and EURO VI diesel vehicles are affected by great uncertainty (Delgado & Muncrief, 2015; EMEP/EEA, 2019).

In addition to the previous considerations, which favor the use of LNG-powered engines, it is necessary to account for some issues that penalize the use of methane-powered engines. As for traditional engines,

Table 7
Percentage changes in total annual emissions - thermoelectric sector.

	Percentage variations - Thermoelectric sector		
	Reference year 2019	LP 2030	HP 2030
$PM_{2.5}$	–	−17	−70
PM_{10}	–	−17	−70
NO_x	–	+1.5	+6
SO_x	–	−17	−72
CO	–	−0.69	−3
CO_2	–	−9.0	−38

there are similar observations about the magnitude and uncertainty pertaining those limiting factors (Clairotte et al., 2020; Vermeulen, 2019).

Considering NO_x emissions, LGN-powered heavy vehicles are slightly penalized compared to conventional internal combustion engines (Cornelis, 2019).

Finally, one can focus on hydrocarbon and methane emissions. These losses are, for example, frequent during tank loading and unloading operations, or during refueling phases. Given the gaseous nature of methane, it is more easily subject to accidental emission phenomena. This penalizes methane engines severely, up to off balancing the advantages obtained in relation to CO_2 and particulate emissions. This topic is covered by an ample and complex literature, which shows a wide dispersion of the results. This apparently indicates a controversial issue, but it simply highlights the uncertainty of the experimental results.

However, referring mainly to the work of Vermeulen et al. (2017), it is possible to identify a unitary reduction contribution (expressed in g/km) for each pollutant proposed. Those basic elements are considered generated by comparing the emissions from a methane vehicle to the same quantity referred to a EURO VI vehicle. In this way the following parameters can be calculated:

- CO_2: −10 %;
- Particulate matters: −15 %;
- NO_x: +15 %;
- HC: +30 %.

It should be noted that, bearing in mind the considerations expressed beforehand, not all percentage contributions are negative.

For instance, analyzing CO_2 and NO_x emissions, it is possible to calculate the total emission reductions. The forecast scenario can be hypothesized based on data reported in deliverable T3.3.1 developed in the SIGNAL project framework. Following the more optimistic hypothesis, which corresponds to an 18.5 % incidence of LNG-powered vehicles on the total circulating vehicles in 2030, this directly translates into a volume of 54 Mvkm/year. Assuming as average emission factors those reported in the EMEP/EEA (2019):

- NO_x: 33.37 g/kg (diesel oil);
- CO_2: 3.169 kg/kg (diesel oil).

The same document reports as a typical fuel consumption per kilometer (for a heavy-duty vehicle) a value of 240 g diesel/km.

Putting these data together, the following changes in emissions are obtained:

- NO_x: +64.87 t/year
- CO_2: -4107 t/year.

It is necessary to observe that these example values, considering the uncertainties mentioned above, are however three orders of magnitude lower than the contributions related to the sectors analyzed previously (residential, tertiary, industrial, marine transport, and thermoelectric production). Overall, this renders the terrestrial transport sector negligible when calculating the total reduced emissions and, thus, the environmental impacts.

Results – economic benefits

When concern is about environmental emissions, it is worth remembering that the European Union has developed and made operational the first market for greenhouse gas emission certificates (Directive 2003/87/EC). The EU Emission Trading System (ETS) is the main tool adopted by the European Union to achieve the CO_2 reduction targets in the industrial and in the aviation sectors. The ETS constitutes a certificate trading market that considers the economic value of the emissions avoided, and is described in detail in the EU *ETS Handbook* (EC, 2015). The effectiveness of this trading system was estimated in the achievement of a reduction of 3.8 % of global CO_2 emissions in the EU area, if compared to an unregulated scenario (2008–2018) (Bayer & Aklin, 2020). In addition, nowadays it remains the largest environmental certificate exchange market in the world.

The system is based on a mechanism called "*cap & trade*": an overall maximum limit for emissions is set for the sectors concerned (i.e., the "*cap*") to which corresponds an equivalent number of "allowances" (1 t of $CO_{2eq} = 1$ share) that can be bought or sold on a special market (i.e., the "*trade*"). The ETS places a limit on pollutant emissions while promoting practices that lead to virtuous circles for activities with a high environmental impact. United Nations 2030 Agenda for Sustainable Development (UN, 2015).

The trading system was born in 2005, and has been divided into several phases over time:

- 1st phase: 2005–2007;
- 2nd phase: 2008–2012;
- 3rd phase: 2013–2020;
- 4th phase: 2021–2028.

In January 2021, phase 4 began, which is foreseen to reduce emissions by 2.2 % on a yearly basis (compared to 1.74 % for the period 2015–2020) (EU, 2018). Phase four is particularly important as the establishment of a market stabilization mechanism is confirmed, which should prevent excessive fluctuations in the certificate value. This operation is necessary to avoid the odds of periods where there is no interest in producing or acquiring the certificates and, consequently, the monetary value of emission reduction is decreased. In fact, the price of certificates is not constant, but is determined by free market rules underlying the ETS: the certificate price depends on several economic global events. This poses a serious problem that has to be tackled: as an example, the United Kingdom has set a statutory price which must be used in legal proceedings to resolve disputes (Secretary of State for Business, Energy and Industrial Strategy, 2019).

Looking at the historical trends for the certificate price for the ETS market (EMBER, 2022), shown in Fig. 7, it is clear that trends are difficult to predict, but in general there is an increase in value at the beginning and at the end of each phase. As for the minimum and maximum values, it is observed that the price fluctuates with high variability equal to about 1 order of magnitude, going from about 3.5 to about 35 €/t CO_{2eq}.

Looking at the profile, it is possible to identify an overestimation of the price during the beginning of each phase, determined by a preventive acquisition of the certificates.

The variability of certificate price constitutes an issue when long term forecasts must be made. For instance, considering the reduction of 0.9 Mt CO_{2eq} obtained comparing the present-day scenario with the HP scenario (residential, tertiary, industrial and maritime transport sectors), the economical value associated with the environmental benefit could be evaluated as about 10 million euros if the certificates were worth 4 €/t CO_{2eq}, while it would be worth about 80 million euros if the certificates were worth 32 €/t CO_{2eq}. Under these conditions, it is very difficult to meaningfully quantify the economic value corresponding to the CO_2 reduction forecast in the present work, without making an error which could be as large as almost one order of magnitude. Moreover, the prediction of a realistic value for the certificate price would be difficult especially if a time span of 10 years is considered.

Fig. 7. Price history for the ETS certificates, in euros.

Conclusions

This paper focuses on the effects of shifting the current energy mix of Sardinia region towards a new short-term mix in which the share of LNG increases and leads energy mix to a progressive reduction of other fossil fuels.

The paper focuses on the calculation of the emission levels for the six selected compounds ($PM_{2.5}$, PM_{10}, NO_x, SO_x, CO, CO_2) for the tertiary, industrial, residential, and maritime transportation sectors, in case of two different scenarios characterized by two levels of switch to LNG. The first scenario considers a prudent approach to the newly available energy vector, LP, in which 25 % of energy is provided by LNG. The second scenario forecasts a more enthusiastic approach, which generates a level substitution of other fuels in which LNG provides about 60 % of Sardinia's energy consumption. Such different scenarios could not come out of the effects of market considerations alone if they are not triggered and sustained by political actions, such as incentives and exemptions.

In both of the scenarios, a different rate of takeover of NG on other energy sources has been considered for each type of consumer sectors, because of the typical features that distinguish one group of consumers from the others, such as size, access to investment and public incentives, technology availability etc.

In the paper, the effects of this substitution are reported in detail and it can be seen that, in case of transition, there is a net environmental advantage if compared with current conditions.

In both cases, independently of the level of LNG market share, there is a decrease in the total fossil fuel consumption, which is related to the higher efficiency of NG devices in comparison to the other fossil fuel ones. In case of low level of substitution, the total reduction of CO_2 emissions is about 15 % and it rises to 26 % of reduction, in comparison to the 2019 level of emissions, in case of a strong swap to NG.

Looking at the details of the results, it can be seen that major effects are obtained in those sectors in which consumption is higher and the level of technology is lower. On the other hand, in sectors like automotive in which the tech level, driven by tighter environmental rules, is higher, the effect of transition to NG is scarce, if any. In particular, the reduction of NO_x emissions for NG vehicles is negligible in comparison to the car fleet that complies with current and near future norms.

The results are affected by the uncertainties related to the difficulties of defining precise estimations of short-term energy mix of a small region, or to explain it better, it is clear that major uncertainties are contained in the premises of this work rather than in its results. The scenarios that were selected can be considered as “reference conditions” that can be used as a starting point for further refinements, in the next decade, when updated conditions are going to be available, with lower uncertainties. In any case, the current analysis suggests that the adoption of LNG is a step forward to pollution reduction targets set by national and international legislation. In this sense, the transition from solid/liquid fossil fuels to LNG on the Sardinia island can surely contribute to pursue Sustainable Development Goal #7 adopted by all Member States in 2015, which calls for “access to affordable, reliable, sustainable and modern energy for all.”

Finally, the evaluation of the economic benefits bound to the reduction of CO_2 emissions is presented. The procedure refers to the EU ETS (Emission Trading System) market, assigning a value in euros to each tonne of equivalent CO_2 not emitted into the atmosphere, according to the proposed scenarios. This operation, however, is made difficult by the high variability of the value of the certificates traded within the market itself. According to the historical value of the certificates, this variability can be considered equal to a factor of 10. Extra caution should be used in interpreting the results, and when considering certificate price forecasts with a time horizon up to 2030.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

This work was funded by the EU INTERREG IT-FR “Maritime” Programme 2014-2020, and developed within the framework of the cross-border cooperation project SIGNAL (*Strategie transfrontalIere per la valorizzazione del Gas NAturale Liquido* – Cross-border strategies for the valorization of liquefied natural gas), CUP D36C18000260006.

Appendix A

Residential + Tertiary – Sources: EMEP/EEA air pollutant emission inventory guidebook 2019 – Emission factors for electricity production and consumption in Italy (ISPRA) 2019

EMEP/EEA Sector	TIER – Source	Category Fuel TIER 1	fuel	substance	EF value	Um
Residential plants	Tier 2 emission factor	Gas Oil	Diesel Oil	$PM_{2.5}$	1.5	g/GJ
Residential plants	Tier 2 emission factor	Gas Oil	Diesel Oil	PM_{10}	1.5	g/GJ
Residential plants	Tier 2 emission factor	Gas Oil	Diesel Oil	NO_x	69.0	g/GJ
Residential plants	Tier 2 emission factor	Gas Oil	Diesel Oil	SO_x	79.0	g/GJ
Residential plants	Tier 2 emission factor	Gas Oil	Diesel Oil	CO	3.7	g/GJ
N.A.	ISPRA, 19	Gas Oil	Diesel Oil	CO_2	202.9	kg/GJ
Residential plants	Tier 1 emission factor	Gaseous Fuels	LPG	$PM_{2.5}$	1.2	g/GJ
Residential plants	Tier 1 emission factor	Gaseous Fuels	LPG	PM_{10}	1.2	g/GJ
Residential plants	Tier 1 emission factor	Gaseous Fuels	LPG	NO_x	51.0	g/GJ
Residential plants	Tier 1 emission factor	Gaseous Fuels	LPG	SO_x	0.3	g/GJ
Residential plants	Tier 1 emission factor	Gaseous Fuels	LPG	CO	26.0	g/GJ
N.A.	ISPRA, 19	Gaseous Fuels	LPG	CO_2	109.0	kg/GJ
Residential plants	Tier 2 emission factor	Natural Gas	LNG	$PM_{2.5}$	0.2	g/GJ
Residential plants	Tier 2 emission factor	Natural Gas	LNG	PM_{10}	0.2	g/GJ
Residential plants	Tier 2 emission factor	Natural Gas	LNG	NO_x	42.0	g/GJ
Residential plants	Tier 2 emission factor	Natural Gas	LNG	SO_x	0.3	g/GJ
Residential plants	Tier 2 emission factor	Natural Gas	LNG	CO	22.0	g/GJ
N.A.	ISPRA, 19	Natural Gas	LNG	CO_2	102.1	kg/GJ

Industrial – Sources: EMEP/EEA air pollutant emission inventory guidebook 2019 – Emission factors for electricity production and consumption in Italy (ISPRA) 2019

EMEP/EEA Sector	TIER – Source	Category Fuel TIER 1	fuel	substance	EF value	Um
Public electricity and heat production	Tier 1 emission factor	Heavy Fuel Oil	Petroleum coke	$PM_{2.5}$	19.3	g/GJ
Public electricity and heat production	Tier 1 emission factor	Heavy Fuel Oil	Petroleum coke	PM_{10}	25.2	g/GJ
Public electricity and heat production	Tier 1 emission factor	Heavy Fuel Oil	Petroleum coke	NO_x	142.0	g/GJ
Public electricity and heat production	Tier 1 emission factor	Heavy Fuel Oil	Petroleum coke	SO_x	495.0	g/GJ
Public electricity and heat production	Tier 1 emission factor	Heavy Fuel Oil	Petroleum coke	CO	5.0	g/GJ
N.A.	ISPRA, 19	Heavy Fuel Oil	Petroleum coke	CO_2	209.8	kg /GJ
Public electricity and heat production	Tier 1 emission factor	Gas oil	Combustible Oil	$PM_{2.5}$	0.8	g/GJ
Public electricity and heat production	Tier 1 emission factor	Gas oil	Combustible Oil	PM_{10}	3.2	g/GJ
Public electricity and heat production	Tier 1 emission factor	Gas oil	Combustible Oil	NO_x	65.0	g/GJ
Public electricity and heat production	Tier 1 emission factor	Gas oil	Combustible Oil	SO_x	46.5	g/GJ
Public electricity and heat production	Tier 1 emission factor	Gas oil	Combustible Oil	CO	16.2	g/GJ
N.A.	ISPRA, 19	Gas oil	Combustible Oil	CO_2	214.0	kg/GJ
Public electricity and heat production	Tier 1 emission factor	Gaseous fuels	LPG	$PM_{2.5}$	0.89	g/GJ
Public electricity and heat production	Tier 1 emission factor	Gaseous fuels	LPG	PM_{10}	0.89	g/GJ
Public electricity and heat production	Tier 1 emission factor	Gaseous fuels	LPG	NO_x	89.0	g/GJ
Public electricity and heat production	Tier 1 emission factor	Gaseous fuels	LPG	SO_x	0.281	g/GJ
Public electricity and heat production	Tier 1 emission factor	Gaseous fuels	LPG	CO	39.3	g/GJ
N.A.	ISPRA, 19	Gaseous fuels	LPG	CO_2	109.0	kg/GJ
Public electricity and heat production	Tier 2 emission factor	Gaseous Fuels	LNG	$PM_{2.5}$	0.2	g/GJ
Public electricity and heat production	Tier 2 emission factor	Gaseous Fuels	LNG	PM_{10}	0.2	g/GJ
Public electricity and heat production	Tier 2 emission factor	Gaseous Fuels	LNG	NO_x	153.0	g/GJ
Public electricity and heat production	Tier 2 emission factor	Gaseous Fuels	LNG	SO_x	0.281	g/GJ
Public electricity and heat production	Tier 2 emission factor	Gaseous Fuels	LNG	CO	4.8	g/GJ
N.A.	ISPRA, 19	Gaseous Fuels	LNG	CO_2	97.3	kg/GJ

Marine Transport – Sources: EMEP/EEA air pollutant emission inventory guidebook 2019 – IMO Resolution MEPC 245 (66) 2014 'Guidelines on the method of calculation of the attained Energy Efficiency Index (EEDI) for new ships' – Physical Characteristics of Particle Emissions from a Medium Speed Ship Engine Fueled with Natural Gas and Low-Sulfur Liquid Fuels

EMEP/EEA Sector	TIER – Source	Category Fuel TIER 1	fuel	substance	EF value	Um
National navigation	Tier 1 emission factor	Marine diesel oil/marine gas oil (MDO/MGO)	MDO/MGO	$PM_{2.5}$	1.4	kg/t fuel
National navigation	Tier 1 emission factor	Marine diesel oil/marine gas oil (MDO/MGO)	MDO/MGO	PM_{10}	1.5	kg/t fuel
National navigation	Tier 1 emission factor	Marine diesel oil/marine gas oil (MDO/MGO)	MDO/MGO	NO_x	78.5	kg/t fuel
National navigation	Tier 1 emission factor	Marine diesel oil/marine gas oil (MDO/MGO)	MDO/MGO	SO_x	20.0	kg/t fuel
National navigation	Tier 1 emission factor	Marine diesel oil/marine gas oil (MDO/MGO)	MDO/MGO	CO	7.4	kg/t fuel
N.A.	Literature	Marine gas oil	MGO	CO_2	3.1	t/t fuel
N.A.	Literature	Marine diesel oil	MDO	CO_2	3.2	t/t fuel
N.A.	Literature	Natural Gas	LNG	$PM_{2.5}$	0.14	kg/t fuel
N.A.	Literature	Natural Gas	LNG	PM_{10}	0.15	kg/t fuel
N.A.	Literature	Natural Gas	LNG	NO_x	31.4	kg/t fuel
N.A.	Literature	Natural Gas	LNG	SO_x	2.0	kg/t fuel
N.A.	Literature	Natural Gas	LNG	CO	N.A.	kg/t fuel
N.A.	Literature	Natural Gas	LNG	CO_2	2.5	t/t fuel

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