Assessing the potential role of biofuels in future energy scenarios for Italy

Energy Proceedings
Vol 58, 2025
ISSN 2004-2965

Assessing the potential role of biofuels in future energy scenarios for Italy#

Alessio Vai[1,2], Matteo Nicoli[1,2*], Daniele Mosso[2], Laura Savoldi[2], Valeria Di Cosmo[1]

[1] Department of Economics and Statistics "Cognetti de Martiis", Università degli Studi di Torino, Italy

[2] MAHTEP Group, Department of Energy "Galileo Ferraris", Politecnico di Torino, Torino, Italy
(Corresponding Author: matteo.nicoli@polito.it)

ABSTRACT
The transport industry is currently facing significant challenges as it is transitioning toward low-emitting technologies. Uncertainty about the future evolution of the transport sector may discourage the adoption of more sustainable solutions, promoting the continued reliance on fossil-fuel based technologies. Indeed, most of the current investments are devoted to battery electric vehicles, that may represent a valuable solution in specific conditions, such as urban transportation. However, not all the sectors can be efficiently electrified as cars. In this regard, the adoption of sustainable fuels may lead to an emission reduction in both urban and extra urban areas. The deployment of synthetic fuels obtained from CO_2 capture, biofuels and hydrogen may replace the traditional fossil fuels and support the transport electrification. The urgent need to address future uncertainty and identify effective solutions to reduce the transport sector impact can be supported by tools like Energy System Optimization Models. These models enable the optimization of the future evolution of energy systems under specific assumptions. This study aims at identifying potential solutions for decarbonizing the hard-to-abate transport sectors, that cannot be effectively addressed by battery technologies. Focusing on the Italian transport sector, the TEMOA-Italy model is adopted to analyze possible future scenarios involving the deployment of alternative low-emitting fuels.

Keywords: Renewable Energy Resources, Advanced Energy Technologies, Biofuels Production, Transport Sector, Energy Systems, Energy Policies.

NOMENCLATURE

Abbreviations	
AFOLU	Agriculture, Forestry and Other Land Use
BAU	Business As Usual
BEV	Battery Electric Vehicle
ESOM	Energy System Optimization Model
ETBE	Ethyl Tert-Butyl Ether
HVO	Hydrotreated Vegetable Oil
NZE	Net Zero Emission
SAF	Sustainable Aviation Fuel
TEMOA	Tools for Energy Model Optimization and Analysis

1. INTRODUCTION

The achievement of the net zero emission target wished by the European Union must go through the decarbonization of the transport sector, that is responsible for almost a quarter of the global CO_2 emissions [1]. In this regard, Battery Electric Vehicles (BEVs) were identified as a very promising solution in achieving the decarbonization of the transport sector [2], but due to the rising challenges concerning their deployment [3], [4] policymakers may consider incentivizing the adoption of alternative solutions [5]. Indeed, the sustainable electrification of the transport sector needs adequate reinforcement of the supply infrastructure, resulting particularly challenging in isolated regions. In contrast, in urban areas the deployment of BEVs can be incentivized by actions such as vehicle-to-grid [6], promoting users' activity but dramatically increasing the complexity of the infrastructure [7]. These challenges become even more difficult to tackle for the hard-to-abate sectors, that are not suitable for efficient electrification [8]. This condition is particularly representative of the Italian transport sector. In 2023, oil products were the principal resources consumed from the transport sector in Italy, almost the 91%, while electricity covered only the 2% of the total consumptions [9]. In this regard, the deployment of alternative sustainable fuels could support the decarbonization of different sectors. Biofuels could relevantly contribute to reducing the net CO_2 emissions produced from urban transport by capturing a portion of these emissions with crops cultivation in the countryside [8]. Moreover, synthetic fuels produced by carbon

This is a paper for the 11th Applied Energy Symposium: Low Carbon Cities & Urban Energy Systems (CUE2025), July 18-22, 2024, Kitakyushu, Japan.

capture processes and renewable hydrogen can sustain the decarbonization of hard-to-abate transport sectors [10].

The potential future contribution of sustainable alternative fuels is still uncertain, and further studies on their bankability and technology deployment are necessary to define an efficient incentive strategy [11]. In this regard, Energy System Optimization Models (ESOMs) can represent a powerful instrument to support decision makers in defining more aware energy policies [12], [13]. These models rely on a highly detailed database, reporting a precise techno-economic characterization of the entire energy system [14]. Indeed, the model's objective is to satisfy the end-user demands through the commodities produced by the supply side, finding the minimum-cost solution [15].

The focus of the study is to analyze how different sustainable fuels can be deployed in the Italian energy system by applying the biofuels production framework developed from the European Joint Research Center [16] to the open-source Tools for Energy Model Optimization and Analysis (TEMOA) [17]. The study is conducted with the adoption of the TEMOA-Italy model [14], focusing on the decarbonization of the transport sector.

2. MATERIAL AND METHODS

The methodology adopted in this study focuses on introducing comprehensively modeling the bioenergy primary resources and biofuels production options in ESOMs. The bioenergy supply chain reported in Figure 1 shows that the supply is provided by four principal groups of resources: solid biomass, waste, biogas and crops. These resources are defined both for the maximum available supply, due to the land potential and for production costs [18], [19]. The first parameter represents a constraint for the energy model, limiting the resources consumption. The methodology and data adopted to model the biofuel supply chain is derived by the European Joint Research Center [20]. Solid biomass includes different types of woods, agricultural and forestry residues. These resources can be consumed directly in the end-use sectors, such as industry and residential, or can be adopted in the production of hydrogen [21] and biogas, subsequently upgraded to biomethane by CO_2 removal processes. The end-use sectors may also consume waste (e.g. industrial and residential waste) and biogas. On the other hand, crops are involved in the production of biofuels only, such as biodiesel, bioethanol and biokerosene. The modeled crops, such as sugar, starchy and rapeseed, can be used both for food and bioenergy purposes.

Biofuels are produced by different processes that are modeled through biorefinery technologies. The latter can be classified as 1st and 2nd generation refineries. The 1st generation (G1) involves consolidated processes such as transesterification and fermentation to produce biodiesel and bioethanol respectively. Crops consumed in 1st generation refineries, sugar, starchy and rapeseed crops, are also involved in food production, representing a potential limitation for future deployment. In contrast, 2nd generation (G2) processes consume only grassy crops that are not competing with food production. These refineries are still under development (e.g. thermochemical process) [22] and the specifics of both refineries are reported in Table 1.

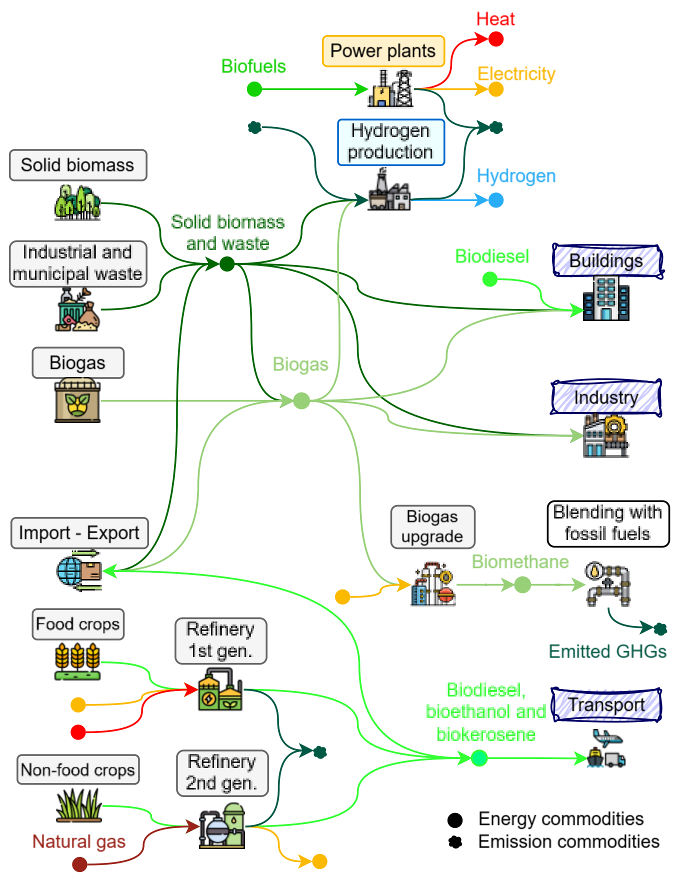

Figure 1. Biofuels supply layout in TEMOA-Italy model.

Biodiesel can be produced from both transesterification of vegetable oil and the processing of grassy crops. Vegetable oil is provided from the refinement of rapeseed crops and from importation, suppling also the production of hydrotreated vegetable oil (HVO). Similarly, bioethanol is produced by starchy and sugar crops fermentation. Furthermore, bioethanol can be also involved in the production of ethyl tert-butyl ether (ETBE) by the addition of isobutylene, providing fuel with higher energy and emission content. The biofuels produced by 2nd generation (e.g. biokerosene) and HVO refineries present properties similar to fossil fuels, allowing higher blending shares (see Table 2).

As extensively discussed in [10], the TEMOA-Italy framework includes also a precise characterization of the synthetic fuels production processes. The CO_2 required in the production of synthetic fuels, such as synmethane, syndiesel and synkerosene can belong from both carbon capture utilization and storage and direct air capture [23]. The sequestrated CO_2 can be subsequently processed with renewable hydrogen in the production of synfuels. Moreover, alternative fuels are blended with fossil fuels, and the maximum blending shares assumed in TEMOA-Italy model are reported in Table 2.

Table 1. Refineries features [20].

Process	Input	Output	Efficiency	Investment Cost (M€/PJ)
Crushing^{+}	Rapeseed crops	Vegetable oil	0.54	
Transesterification^{+}	Vegetable oil	Biodiesel	0.94	1.5 ÷ 1.3
Fermentation^{+}	Starchy crops	Bioethanol	0.34	22.6 ÷ 15.7
	Sugar crops		0.11	8.2 ÷ 5.7
Chemical^{+}	Ethanol	ETBE	0.92	
Hydrotreatment^{+}	Vegetable oil	HVO	0.81	5.8 ÷ 4.2
Thermochemical and biochemical^{++}	Grassy crops	Biodiesel Biokerosene	0.63	180.6
		Bioethanol	0.37	104.9

$^{+}$ 1st generation refinery.
$^{++}$ 2nd generation refinery.

Table 2. Constraints on maximum blending share (in energy terms) of alternative fuels applied in TEMOA-Italy [10].

Alternative Fuels	2020	2025	2030	2050
Hydrogen	1%	2%	6%	6%
Biomethane	0.2%	1%	5%	100%
Biodiesel G1	7%			30%
Biodiesel G2	0%	0%	5%	100%
HVO	0%	0%	5%	100%
Bioethanol	7%			15%
Synthetic ethanol	0%	0%	3%	3%
Other synthetic fuels	0%	0%	5%	100%

3. RESULTS

For this study, the future energy scenarios investigated are the Business As Usual (BAU) and the Net Zero Emission (NZE), defined as in [24]. The BAU scenario considers only constraints aimed at guaranteeing the model calibration, providing the optimal-cost solution through the analyzed time horizon (up to 2050). On the other hand, the NZE scenario is defined according to the European Commission's Fit For 55 package directions [25] (up to 2030) and the Italian long-term strategy (from 2030 up to 2050) for the abatement of greenhouse gases emission [26]. The transport sector fuels consumption is reported in Figure 2, considering both road vehicles (e.g. cars and trucks) and non-road vehicles (e.g. aviation and naval) [27]. Fossil fuels still represent the principal alternative in the BAU scenario (see Figure 2a). Indeed, diesel, gasoline and kerosene cover the higher fraction of the consumption, with an average of 900, 320 and 375 PJ respectively toward the 2030-2050 period. Only biodiesel is adopted by the model as alternative fuel, reaching the maximum consumption of more than 90 PJ in 2050. In contrast, the fossil fuels consumption observed in the NZE scenario (see Figure 2b) are strongly reduced due to the constraints on the CO_2 emissions.

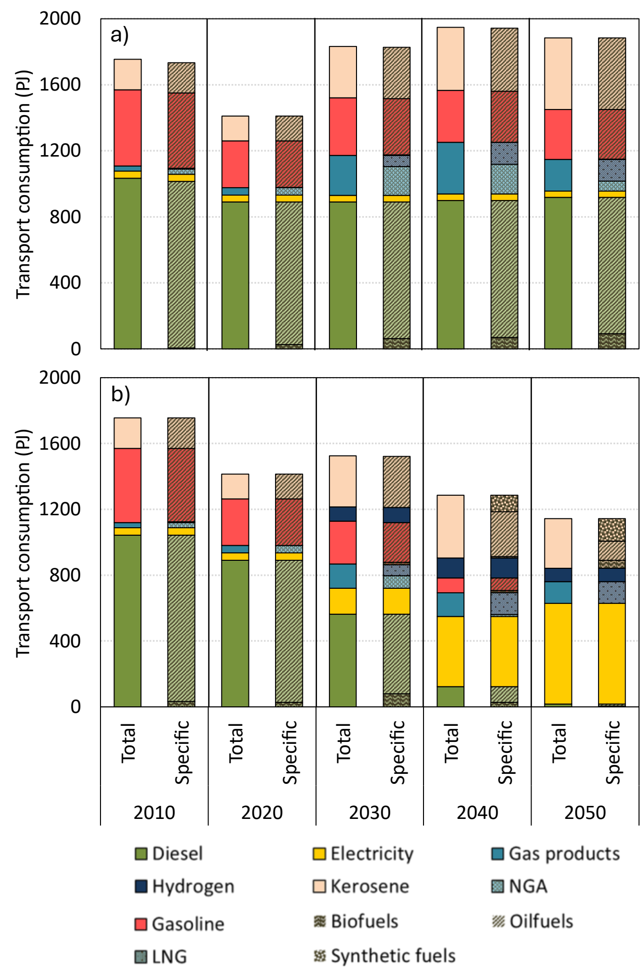

Figure 2. Transport sector total and specific (bio, oil and synthetic) fuels consumption for BAU (a) and NZE (b) scenarios.

From 2030 up to 2050 the overall transport consumptions are quite reduced, moving from more than 1500 PJ in 2030 to almost 1150 PJ in 2050. This reduction is due to the penetration of electric vehicles and their higher efficiency with respect to traditional vehicles. In this regard, the electricity consumed in 2050 by the transport sector in the NZE scenario is more than 600 PJ, almost 16 times higher than in BAU (38 PJ). In the decarbonized scenario there is also a higher fraction of alternative fuels consumption, especially of biokerosene and synthetic kerosene, reaching 50 and 140 PJ respectively.

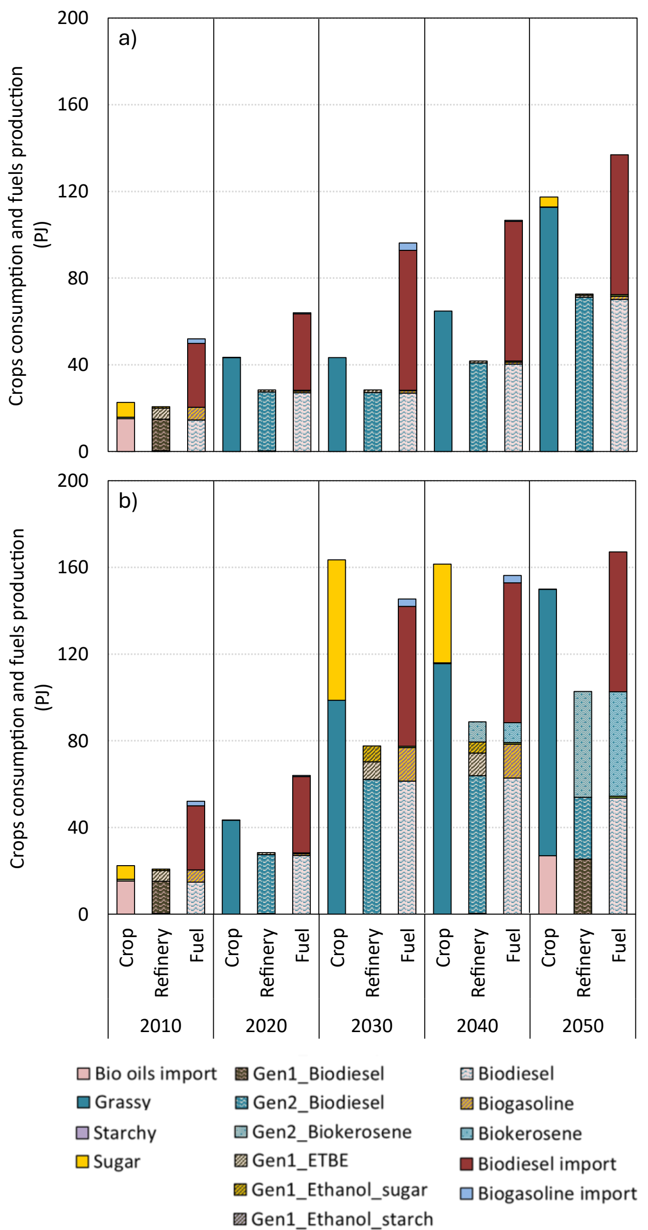

Figure 3. The crops consumption is reported in the first column, while the refineries activity and the biofuels production and import are represented by the second and third column respectively, for both BAU (a) and NZE (b) scenarios.

In the model, biofuels are produced exclusively from biorefineries through the consumption of crops. The refineries activity is reported in Figure 3, showing also the crops consumption and the refinery biofuels production. In the NZE scenario (Figure 3b), the crops consumption is much higher than in BAU (Figure 3a), especially in 2030 and 2040. In these periods, grassy and sugar crops represent the principal feedstocks to produce biodiesel and bioethanol in NZE, with a consumption of approximately 100 PJ (7870 kt) in 2030 and 116 PJ (9210 kt) in 2040 of grassy crops (considering an energy content of 12.5 kJ/kg). The latter are consumed principally in 2[nd] generation refineries to produce biodiesel, while by 2040 grassy crops are also involved in the production of biokerosene, with almost 48 PJ produced in 2050.

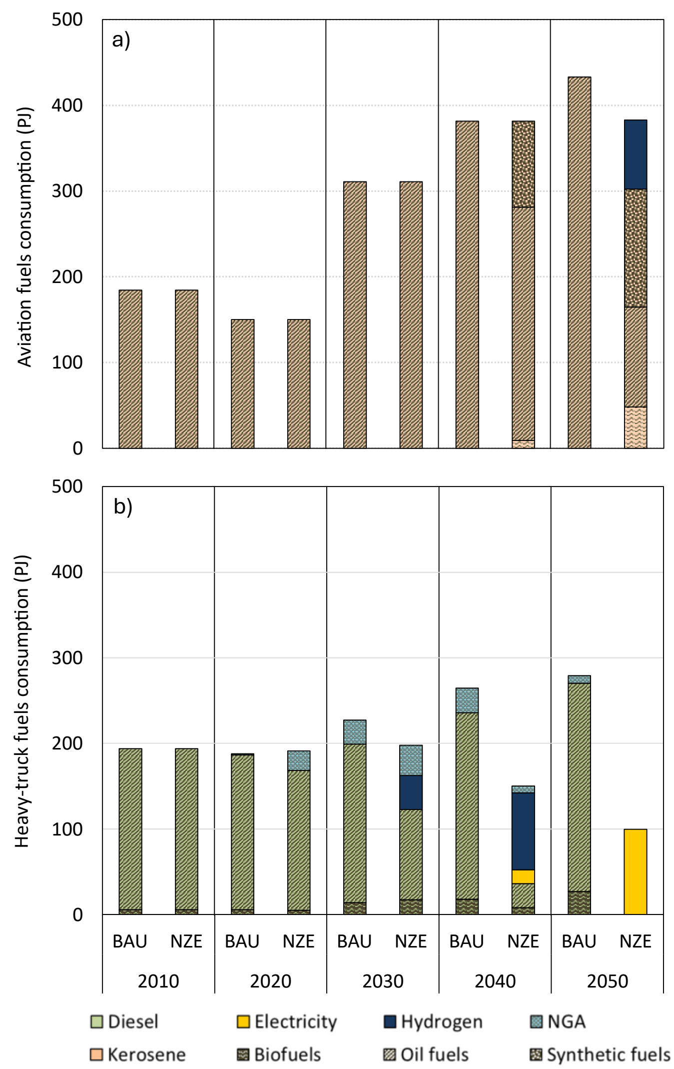

Figure 4. Fuels consumption in the aviation (a) and heavy-truck (b) transportation in the BAU and NZE scenarios.

On the other hand, sugar crops are adopted only in the production of bioethanol, with a consumption of approximately 65 PJ (3900 kt) in 2030 and 46 PJ (2750 kt) in 2040 (considering an energy content of 16.6 kJ/kg). In contrast, grassy crops are the principal feedstock consumed in the BAU scenario, reaching the highest consumption in 2050, almost 113 PJ (8990 kt), to produce biodiesel. In BAU, in 2050 almost 68% of biodiesel is consumed in the transport sector, while for the NZE scenario this fraction is reduced to 4% and the majority of biodiesel is consumed by other transformation sectors. This reduction is due to the high electrification of transports induced by the emission reduction trajectory to be achieved and given the constraints on the maximum share of biofuels (see Table 2), limiting the potential GHGs reduction benefit associated with their share in the fuel mix. As observed in Figure 4b, the heavy-truck transport sector is moving towards complete electrification by 2050. Indeed, the alternative fuels consumption is approximately 57 PJ (17 PJ of biodiesel and 40 PJ of hydrogen) in 2030 and 98 PJ (8 PJ of biodiesel and 80 PJ of hydrogen) in 2040. The hydrogen consumed from the transport sector is produced by steam reforming and the gasification of solid biomass, that are CO_2 emissive processes. Due to these emissions, the heavy-truck sector is completely electrified in 2050, reaching an electricity consumption of approximately 100 PJ. On the other hand, the hydrogen produced in 2050 is mainly adopted in the aviation sector (see Figure 4a), with a consumption of more than 80 PJ.

Moreover, biokerosene and synthetic kerosene are consumed by 2040, approximately 10 PJ and 100 PJ respectively. In 2050, sustainable aviation fuels (SAFs) consumption increases, with more than 40 PJ of biokerosene and 130 PJ of synthetic kerosene. Furthermore, in 2050 hydrogen is contributing to the decarbonization of the aviation sector, supplying domestic aircraft only and covering almost 20% of the total fuels consumption. Being the aviation sector not suitable for efficient electrification, SAFs may represent a powerful alternative for the aviation decarbonization [28]. These results are obtained under specific assumptions on primary resources availability, emission factors for their production and techno-economic parameters. These assumptions can be further investigated by enhancing the model's projections.

4. CONCLUSIONS AND PERSPECTIVES

In this study, the potential role that biofuels may have in supporting the decarbonization of the hard-to-abate transport sectors in the Italian energy system is analyzed. As observed in the results, biofuels play only a marginal role in the achievement of net-zero emission target. However, in the decarbonization of the aviation industry, biofuels coupled with other low-carbon fuels, such as synthetic fuels and hydrogen, are expected to play a pivotal role. In contrast, in the heavy-truck transportation biofuels are deployed only in the near-future (2030-2040), while a complete electrification of the sector is observed at the end of the time horizon (2050). The role of biofuels and other sustainable fuels may relevantly change when a limited electrification of the transport sector is considered and in the case of higher alternative fuel shares can be deployed by transport technologies (e.g., for renewable hydrocarbons [29]).

The potential role that alternative fuels may have in decarbonizing the hard-to-abate sectors can be analyzed deeper by modeling incentives aimed at promoting the production and adoption of sustainable fuels. The potential impact of different assumptions than net-zero concerning the net emissions associated with the biofuels supply chain should be explored too, for instance including factors accounting for the emissions due to the production of primary resources and investigating the results sensitivity to them. Furthermore, the promotion of renewable fuels can be coupled with disincentivizing actions to discourage CO_2 production, such as carbon taxes. Additionally, the methodology adopted to define the biofuel supply to the system can be improved, as well as the biorefinery techno-economic definition. The supply side can be modeled through an Agriculture, Forestry and Other Land Use (AFOLU) sector, providing more precise results on the role of bioresources in the decarbonization of the energy systems.

FUNDING

Alessio Vai acknowledges financial support from the National Recovery and Resilience Plan (NRRP), Mission 4 Component 2 Investment 1.4 - Call for tender No. 3138 of December 16, 2021 of the Italian Ministry of University and Research, funded by the European Union - NextGenerationEU (Award Number: CNMS named MOST, Concession Decree No. 1033 of June 17, 2022, adopted by the Italian Ministry of University and Research, CUP: D13C22001290006, Spoke 14 “Hydrogen and New Fuels”).
The work by Matteo Nicoli and Valeria Di Cosmo was funded by the European Union - NextGenerationEU, in the framework of the GRINS - Growing Resilient,

Inclusive and Sustainable project (GRINS PE00000018 – CUP D13C22002160001). The views and opinions expressed are solely those of the authors and do not necessarily reflect those of the European Union, nor can the European Union be held responsible for them.

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