Energy Proceedings
Vol 47, 2024
ISSN 2004-2965

The Energy Transition in the Age of Open Science: Call for Regional Modelling Solutions

Farzaneh Amir Kavei [1,2,*], Matteo Nicoli [2], Francesco Quatraro [1], Laura Savoldi [2]

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

2 MAHTEP Group, Dipartimento Energia "Galileo Ferraris", Politecnico di Torino, Torino, Italy

(* Corresponding Author: farzaneh.amirkavei@unito.it)

ABSTRACT

This work introduces a regional energy model, emphasizing the importance of localized approaches to sustainability. It highlights the significance of energy system models in guiding the energy transitions policies, underscoring the influence of open science on advancing modelling techniques. The open-source energy models can play an important role in developing regional frameworks, which offer more precise insights into the characteristics and challenges of specific areas. The paper introduces TEMOA-Piedmont, the first energy system model of the Piedmont region in Italy, developed within the TEMOA optimization tool. The model aims to bridge national and regional energy policies by providing a detailed analysis of the region's energy structure. The presented results focus on the transport sector, highly impacting the urban environments within the Piedmont region (e.g., the city of Turin) and object of the energy policies due to its criticality for the region. Developed based on totally publicly available data, TEMOA-Piedmont offers a valuable tool for policymakers and stakeholders to step towards a sustainable energy future tailored to the Piedmont region's needs.

Keywords: Local Energy Systems, Open-Source Energy System Optimization Model, TEMOA, TEMOA-Piedmont, Low Carbon Scenario Analysis

NOMENCLATURE

Abbreviations	
ACI	Italian Automobile Club
BS	Baseline Scenario
ELC	Electricity
ESM	Energy System Model
ESOM	Energy System Optimization Model
ET	Emission Transport Scenario
GDP	Gross Domestic Product
GHG	Greenhouse Gas
GSE	Manager of Energy Services
GSL	Gasoline (Petrol)
O&M	Operation & Maintenance
PEAR	Regional Energy and Environmental Plan
TEMOA	Tools for Energy Model Optimization and Analysis

1. INTRODUCTION

The energy transition requires localized shifts towards more sustainable energy resources, which are adapted to the features and needs of specific geographical areas [1]. Unlike national or global policies that focus on a broad framework, regional policies have the privilege of being able to focus on specific opportunities and challenges of a given territory.

Energy System Models (ESMs) are important tools [2] used to assess the long-term implications and the techno-economic requirements of energy transition policies [3], [4]. Open-source ESMs can promote the development of regional models, which currently are very limited or lacking, to our best knowledge. Regional ESMs have several advantages over the national ones, as they more accurately represent the diverse techno-economic characteristics and energy consumption patterns of specific regions. They can consider, for instance, local activities (e.g. minor industrial sectors), which may be disregarded at the national level. Furthermore, regional models are better able to address emission sources, sinks and decarbonization opportunities tailored to region specific urban and industrial structures.

The objective of this work is establishing a connection between national and regional energy and environmental policies by introducing TEMOA-

This is a paper for the 10th Applied Energy Symposium: Low Carbon Cities & Urban Energy Systems (CUE2024), May. 11-12, 2024, Shenzhen, China.

Piedmont, the first regional Energy System Optimization Model (ESOM) of the Piedmont region in Italy. Piedmont is relevant in the Italian context for its high industrialization and dense population. Indeed, its predominantly mountainous and hilly terrain makes it the Italy's third-largest producer of hydroelectric power [5]. Piedmont is home to over 4.26 million people as of 2021 [6], with a GDP of €136.8 billion [7], representing nearly 8% of the national total, placed it fifth among the twenty Italian regions. Manufacturing, food and agriculture, textiles, and electronics are major contributors to the regional economy [7], and they represent a possible development of the model including minor energy sub-sectors.

Like other ESOMs, TEMOA-Piedmont adopts a bottom-up approach to reach the energy system configuration corresponding to the minimum cost and relies on detailed technological and economic data. The model is here used to implement a scenario from the regional transport plan addressing the sector's emissions. The analysis enables the assessment of the technology shift required by such an emission reduction, and the associated costs.

ESOMs are valuable tools for assessing the optimal evolution of energy systems based on future projections of socio-economic factors (like GDP and population), technological advancements (e.g., efficiency improvements and cost reductions), and various scenarios. The model's objective function is the total cost of the energy system, consisting of three cost components: investment costs (€/capita), annual fixed operation and maintenance (O&M) costs (€/capita), and variable O&M costs (€/activity). Greenhouse gas (GHG) emissions are incorporated through emission factors linked to specific commodity consumption or technology activity.

Among several open-source, open-data ESOMs, TEMOA [8] was chosen for developing the Piedmont model. This selection was based on its successful application in a complex case study involving the Italian energy system [9], benchmarking favorably against the TIMES Model Generator [10].

2. METHODOLOGY

The overall frame of the TEMOA-Piedmont is inspired by the TEMOA-Italy one [9], [11], modified to adequately feature the Piedmont region.

The model elaboration starts with the choice of the milestone years, constituting the model time horizon. The model's base year is 2011, while the other time periods involve selected years both in the past and in the

Table 1 Overview of the sectorial allocation of energy commodities consumption

	Residential	**Commercial**	**Agriculture**	**Industry**	**Power**	**Transport**
Electricity	17.90	20.53	1.17	47.38		4.60
Natural Gas	*72.72 (49%)*	*43.63 (29%)*	*29.09 (19%)*	43.42	115.22	*0.92 (3%)*
Diesel	*2.06 (50%)*	*0.66 (30%)*	*6.02 (20%)*	1.79		81.86
LPG	*3.92 (70%)*	*0.56 (10%)*	*0.56 (10%)*	*0.56 (10%)*		3.96
Heavy Fuel Oil	*0.37 (10%)*	*0.37 (10%)*		*2.98 (80%)*		
Gasoline						*30.09 (100%)*
Jet Kerosene						*2.22 (100%)*

future (up to 2050) based on the available energy statistics (statistics for 2023 are not available yet) [12]. The sub-annual resolution of the model includes four seasons (spring, summer, fall, and winter) and four times of day (night, morning, noon, and afternoon).

The energy balance of the region in the base year has been built following a bottom-up approach thus statistics of different energy carriers (e.g., natural gas, electricity etc.) published by different authorities have been referred to. In this way, the data granularity variation across different resources needed to be overcome. Electricity data, obtained from the Italian Transmission System Operator (TERNA) statistics [22], provides the most detailed breakdown. To disaggregate other energy commodities data among sectors, some additional assumptions were necessary. Table 1 summarizes the known values, and the assumed shares adopted to disaggregate the aggregated values across the model's sectors, where needed. The table clearly differentiates known values (without parentheses) from assumed shares (percentages in parentheses), used to rescale the cumulative values reported in the statistics.

To benchmark the data constructed with the above-mentioned method, a crosscheck between them and the available data delivered in the Regional Energy and Environmental Plan (PEAR) [13] has been performed. Fig. 1 Comparison between the energy balance of the final energy consumption mixes in the base year for the TEMA-Piedmont model and the PEAR dataset Fig. 1 shows a comparison between the two datasets. The method leads to 13.6 PJ overestimation of the final

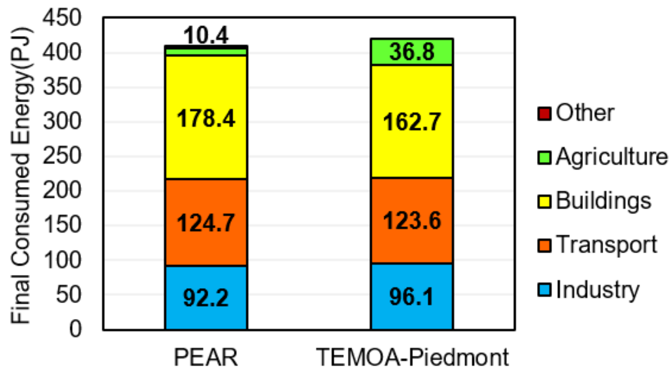

Fig. 1 Comparison between the energy balance of the final energy consumption mixes in the base year for the TEMA-Piedmont model and the PEAR dataset

energy consumption (corresponding to about 3%). As the statistics of PEAR are delivered as cumulative value per sector without distinguishing between energy carriers, spotting the origin of differences was impossible.

Additional steps were needed to further divide the energy carriers among the subsectors of each sector: the present paper focuses on the development criteria of the transport sector.

Land transport is divided into road and rail categories, with the latter encompassing all domestic and international passenger and goods transport services. Road transport, on the other hand, includes separate services for passenger and freight transportation. The aviation sub-sector in the model includes domestic and international passenger and freight services.

Regarding the energy commodities allocation in the base year (2011), electricity, besides rail transport, was attributed just to the non-transport purposes in the sector (see Table 1), due to the limited presence of the electric vehicles in the region in base year [14]. The data relative to the electricity consumption in railways was taken from TERNA [5] and the rest has been attributed to the other electric services. Diesel fuel was the principal fuel input into the sector, followed by petrol, electricity, and LPG. As for petrol consumption, it has been allocated entirely to road transport, as stated in the report of the Regional Environmental Agency [15] and cross-checked with the TEMOA-Italy transport sector [11], based on the IEA energy balance for Italy [16]. All Jet kerosene consumed in the region, obtained from a report of Manager of Energy Services (GSE) [17], was attributed to the aviation sector.

The technological structure of the road sector is identified using the statistics of the Italian Automobile Club (ACI) [14]. Road passenger transport can be carried out using various technologies, such as cars, buses, and

Table 2 Final energy consumptions and demand of the transport sector in the base year (2011).

Sub-sector	Technology	Final Energy Consumption (PJ)						Demand	
		Diesel Fuel	Gasoline	LPG	Natural Gas	Jet Kerosene	Electricity		
Road	Cars	39.5	25.6	4.0	0.9			22.7	Bvkm
	Buses	2.1						0.1	
	Two Wheels		3.5					4.3	
	Light Trucks	19.7	0.9					5.1	
	Medium Trucks	6.1						0.5	
	Heavy Trucks	14.0						0.6	
Rail	Trains	0.6					1.5	2.1	PJ
Aviation	Aircrafts					2.2		2.2	
Other							1.6	1.6	

two-wheelers. Thus, it was necessary to estimate the energy consumption for each vehicle type. It is worth noting that this can't be obtained by disaggregating the energy carriers using the number of the different technology types as it is not a representative factor for the consumptions. Therefore, the task was performed using the national mileage (kilometers travelled) of the specific technologies of the transport sector of TEMOA-Italy in 2006 and their relative numbers in 2006 [18] and 2011 [19]. These data and the same regional statistics were used to rescale the national mileages into regional ones. The outcome of this procedure is shown in Table 2, where the subsectors of the transport sector, their technologies, final fuel consumptions, and the final demands of the sector are reported.

The new technologies of the cars subsector, the most energy consuming among the transport sector, are visible in Table 3, together with their technical and economic parameters. Once the final service demands of all sectors in the base year were calculated, they needed to be projected for the milestone years of the model. This is done with the aid of elasticities and drivers allocated for every demand individually. The demand projection formula in ESOMs has a recursive nature and is shown in Eq. 1, where δ denotes the driver, ε is its elasticity and t refer to the yearly time step.

$$D_t = D_{t-1} \times \left[1 + \left(\frac{\delta_t}{\delta_{t-1}} - 1\right) \times \varepsilon_t\right] \qquad \textit{Eq. 1}$$

Table 3 New technologies of the car subsector and their techno-economic characterization

Category	Technology	Efficiency (Bvkm/PJ)		Investment Cost (M€/Bvkm)		Fixed O&M Cost (M€/Bvkm)	Lifetime
		2020	2050	2020	2050		
Cars	Diesel	0.80	0.98	3090	3060	62.63	12
	GSL	0.31	0.42	2860	2830	62.63	12
	LPG	0.29	0.29	3060	3060	64.37	12
	Natural Gas	0.15	0.20	3060	3060	64.37	12
	Full Hybrid	0.40	0.69	3585	2830	61.76	12
	Plug-in Hybrid	0.76	1.03	5380	3740	60.00	12
	ELC	1.15	1.37	5520	3730	51.33	12
	Fuel Cells	0.50	0.94	11590	5140	70.03	12

The drivers span from GDP to population and added values of different economic sectors. Most of the drivers of TEMOA-Piedmont are obtained from the regional data [7], while the elasticities and some lacking future projections of added values were adopted from TEMOA-Italy [11]. The trend of all drivers of the model is shown in Fig. 2.

3. RESULTS

3.1. The studied scenarios

The TEMOA-Piedmont model is applied to investigate two scenarios:

- A Baseline scenario (BS), which replicates the historical trends in energy production and consumption across various sectors and projects how these trends would continue to evolve under current conditions. It serves as a benchmark for other implemented scenarios and represents the optimal structure of the energy system without implementing any kind of restrictions.
- A scenario specifically designed to explore the implications of the region's transition plans [20]. This scenario, named Emissions Transport (ET), allows to analyze how the transport sector might evolve under the plan's emission limits, as Piedmont region faces significant challenges of high [21] and persistent [22] air pollution. The region's current transport plan, established in 2018 [20], outlines CO2 equivalent ($CO2_{EQ}$) emission targets for 2020, 2030, and 2050, all compared to a 2010 baseline of 9.7 Mt/year. The emission targets are represented as the maximum allowable emissions, expressed as a percentage of the 2010 level.

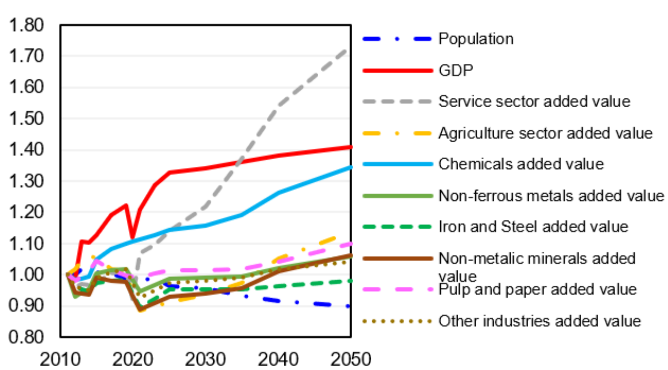

Fig. 2 Demand drivers of the model.

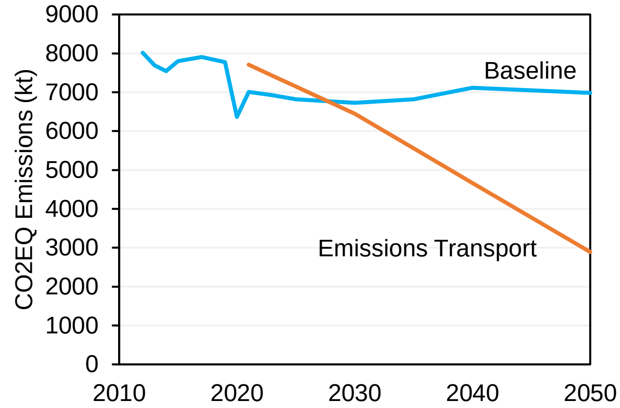

Fig. 3 CO2EQ emissions in the Baseline and Emissions Transport scenarios

The applied scenarios are shown in Fig. 3. It is important to note that the slightly higher starting point for emissions in the ET scenario, if compared to the BS, is due to the referral to the 2010 values. Specifically, the ET scenario applies a -2% reduction in 2020, followed by -20% in 2030, and a significant -63% reduction by 2050, based on [20]. Within the model, this scenario involves setting a cap on the transportation sector's $CO2_{EQ}$ emissions starting from 2021, which gradually decreases, in accordance with the established targets.

3.2. The results

Fig. 4 illustrates the difference between the progression of final energy consumption and $CO2_{EQ}$ emissions within the transport sector under the BS and ET scenarios. The BS maintains a similar energy composition to historical trends, albeit with a larger reliance on gasoline due to its lower investment costs compared to the diesel fuel, especially with the competitive edge of full hybrid cars in recent years. Nonetheless, diesel fuel remains essential for road freight transport via diesel trucks. As opposed to that, the ET scenario in 2050 demonstrates increased adoption of biodiesel fuel and substantial integration of electricity into the energy mix. The incorporation of electric vehicles enhances sector efficiency, resulting in a 33% reduction in the total final energy consumption by 2050 compared to the BS. Emissions are also markedly lower in the ET scenario, adhering to the emission limit outlined in Fig. 3. The remaining emissions primarily stem from fossil diesel fuel and gasoline use, with biodiesel contributing to emissions reduction due to its carbon-neutral status in the model's emission accounting methodology (see [23], [24]).

Despite the additional investment costs associated with deploying electric vehicles in the ET scenario, totaling 4.2 B€ over the 2023-2050 period, the overall system cost difference between the two scenarios narrows to 2.6 B€. This reduction is attributable to savings in fuel costs, partially offsetting the higher investment required for electric vehicles. Further analysis, particularly focusing on the assumptions concerning technology hurdle rates as discussed in [25], could provide deeper insights into these outcomes.

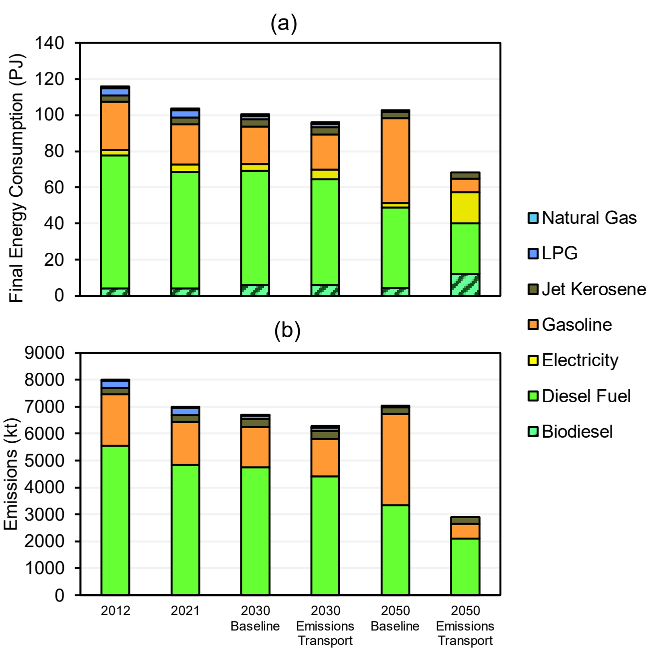

Fig. 4 Breakdown of final energy consumption by energy commodity (a) and of the CO_{2EQ} emissions (b) of the TEMOA-Piedmont transport sector in selected years, in the BS and TE scenarios

4. CONCLUSIONS

The role of specific territories in shaping transition targets is undeniable, for they usually provide unique key-opportunities and transition paths neglected in the national contexts because of their reduced scale. Regional solutions thus call for dedicated energy modelling.

The open-source energy models, despite their young age, showed themselves to be able to promote energy system modelling by conferring accessible frameworks and explorable inputs and outputs. Besides being reliable, these frameworks were shown to be suitable to fill the gap between national and regional energy and environmental monitoring and policies.

The TEMOA-Piedmont energy system optimization model dealing with the Piedmont region in Italy is introduced as the first open-source, open data model of an Italian region. The model is adopted to examine scenarios relative to emission reduction of the transport sector enabling monitoring both energy and technology mix changes to fulfill the implemented emission reduction scenario. Being the first of its kind and developed using fully publicly available data, the model requires further updates and enhancements. Moreover, the framework is planned to be extended by adding water and land dimensions to the energy one.

ACKNOWLEDGEMENTS

The authors express their gratitude to the MAHTEP Group members @PoliTo for their valuable support and contributions during the various stages of model development.

REFERENCE

[1] L. Boisgibault and F. Al Kabbani, "Energy transition in metropolises, rural areas and deserts," *Energy Transition in Metropolises, Rural Areas and Deserts*, pp. 1–224, Jan. 2020, doi: 10.1002/9781119694892.

[2] International Energy Agency (IEA), "Global Energy and Climate Model – Analysis - IEA." Accessed: Mar. 19, 2024. [Online]. Available: https://www.iea.org/reports/global-energy-and-climate-model

[3] A. Chiodi, G. Giannakidis, M. Labriet, B. Gallachóir, and G. C. Tosato, "Introduction: Energy systems modelling for decision-making," in *Lecture Notes in Energy*, vol. 30, Springer Verlag, 2015, pp. 1–12. doi: 10.1007/978-3-319-16540-0_1.

[4] M. Gargiulo, B. Brian´, B. Gallachóir, and G. Gallachóir, "Long-term energy models: Principles, characteristics, focus, and limitations," *Wiley Interdiscip Rev Energy Environ*, vol. 2, no. 2, pp. 158–177, Mar. 2013, doi: 10.1002/WENE.62.

[5] Terna, “Statistical Publications.” Accessed: Jul. 10, 2023. [Online]. Available: https://www.terna.it/en/electric-system/statistical-data-forecast/statistical-publications
[6] Istat, “La superficie dei comuni, delle provincie e delle regioni italiane,” 2013. Accessed: Mar. 16, 2024. [Online]. Available: https://www.istat.it/it/files/2015/04/Superfici-delle-unit%C3%A0-amministrative-Testo-integrale.pdf
[7] Regione Piemonte, “‘I numeri del Piemonte’ - Annuario Statistico Regionale.” Accessed: Mar. 16, 2024. [Online]. Available: https://www.regione.piemonte.it/web/amministrazione/finanza-programmazione-statistica/statistica/numeri-piemonte-annuario-statistico-regionale
[8] TemoaProject, “GitHub - TemoaProject/temoa,” GitHub. Accessed: Feb. 11, 2023. [Online]. Available: https://github.com/TemoaProject/temoa
[9] M. Nicoli, F. Gracceva, D. Lerede, and L. Savoldi, “Can We Rely on Open-Source Energy System Optimization Models? The TEMOA-Italy Case Study,” *Energies (Basel)*, vol. 15, no. 18, p. 6505, Sep. 2022, doi: 10.3390/en15186505.
[10] National Agency for New Technologies Energy and Sustainable Economic Development (ENEA), “The TIMES-Italy Energy Model Structure and Data 2010 Version,” Rome, 2011. Accessed: Sep. 02, 2022. [Online]. Available: https://biblioteca.bologna.enea.it/RT/2011/2011_9_ENEA.pdf
[11] MAHTEP Group, “MAHTEP/TEMOA-Italy,” GitHub. Accessed: May 11, 2022. [Online]. Available: https://github.com/MAHTEP/TEMOA-Italy
[12] Eurostat, “Energy balances - Energy - Eurostat.” Accessed: Aug. 19, 2022. [Online]. Available: https://ec.europa.eu/eurostat/web/energy/data/energy-balances
[13] Regione Piemonte, “Piano Energetico Ambientale Regionale (PEAR),” 2022. Accessed: Mar. 16, 2024. [Online]. Available: https://www.regione.piemonte.it/web/temi/sviluppo/sviluppo-energetico-sostenibile/piano-energetico-ambientale-regionale-pear
[14] Automobile Club d’Italia, “Autoritratto.” Accessed: Mar. 16, 2024. [Online]. Available: https://www.aci.it/laci/studi-e-ricerche/dati-e-statistiche/autoritratto.html
[15] M. Cuviello *et al.*, “Uso delle Risorce - Energia,” Regione Piemonte - Arpa Piemonte. Accessed: Mar. 21, 2024. [Online]. Available: moz-extension://7ef240db-8c22-45c7-8b08-93fc3f667cab/enhanced-reader.html?openApp&pdf=https%3A%2F%2Fwww.arpa.piemonte.it%2Freporting%2Frapporto-sullo-stato-dellambiente-2013%2Frsa_2013_energia
[16] International Energy Agency (IEA), “World Energy Balances - Data product,” International Energy Agency (IEA). Accessed: Mar. 21, 2024. [Online]. Available: https://www.iea.org/data-and-statistics/data-product/world-energy-balances
[17] GSE, “Rapporto statistico 2011 Impianti a fonti rinnovabili,” 2011.
[18] Automobile Club d’Italia, “Autoritratto 2006.” Accessed: Mar. 16, 2024. [Online]. Available: https://www.aci.it/laci/studi-e-ricerche/dati-e-statistiche/autoritratto/autoritratto-2006.html
[19] Automobile Club d’Italia, “Autoritratto 2011.” Accessed: Mar. 16, 2024. [Online]. Available: https://www.aci.it/laci/studi-e-ricerche/dati-e-statistiche/autoritratto/autoritratto-2011.html
[20] Regione Piemonte, “Il Piano Regionale della Mobilità e dei Trasporti | Regione Piemonte.” Accessed: Mar. 21, 2024. [Online]. Available: https://www.regione.piemonte.it/web/temi/mobilita-trasporti/pianificazione-della-mobilita-dei-trasporti/piano-regionale-della-mobilita-dei-trasporti
[21] K. Raffaelli, M. Deserti, M. Stortini, R. Amorati, M. Vasconi, and G. Giovannini, “Improving Air Quality in the Po Valley, Italy: Some Results by the LIFE-IP-PREPAIR Project,” *Atmosphere 2020, Vol. 11, Page 429*, vol. 11, no. 4, p. 429, Apr. 2020, doi: 10.3390/ATMOS11040429.
[22] European Space Agency, “ESA - Air pollution fluctuations over the Po Valley.” Accessed: Mar. 21, 2024. [Online]. Available: https://www.esa.int/Applications/Observing_the_Earth/Air_pollution_fluctuations_over_the_Po_Valley
[23] G. Colucci, D. Lerede, M. Nicoli, and L. Savoldi, “A dynamic accounting method for CO2 emissions to assess the penetration of low-carbon fuels: application to the TEMOA-Italy energy system optimization model,” *Appl Energy*, vol. 352, no.

121951, Dec. 2023, doi: 10.1016/j.apenergy.2023.121951.

[24] G. Colucci, D. Lerede, M. Nicoli, and L. Savoldi, "Dynamic Accounting for End-Use CO2 Emissions From Low-Carbon Fuels in Energy System Optimization Models," *Energy Proceedings*, vol. 29, 2022, doi: 10.46855/energy-proceedings-10294.

[25] S. Laera, G. Colucci, V. Di Cosmo, D. Lerede, M. Nicoli, and L. Savoldi, "Technology-specific hurdle rates for Energy System Optimization Models," *Energy Proceedings*, vol. 39, 2024, doi: 10.46855/energy-proceedings-10911.