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Evaluating the impact of hurdle rates on the Italian energy transition through TEMOA☆

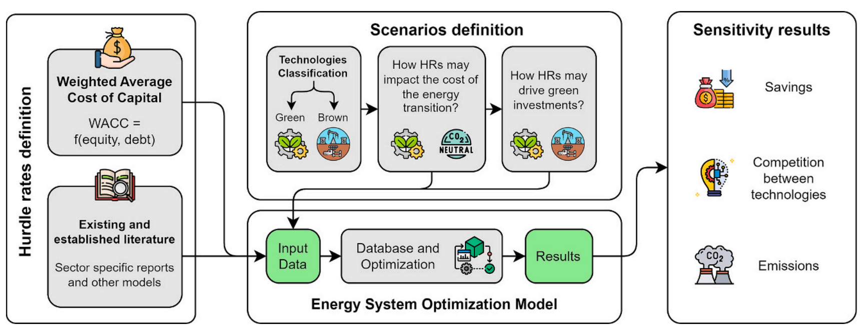
Matteo Nicoli [a,*], Gianvito Colucci [a], Valeria Di Cosmo [b], Daniele Lerede [a,b], Laura Savoldi [a]

[a] *MAHTEP Group, Dipartimento Energia "Galileo Ferraris", Politecnico di Torino, Torino, Italy*
[b] *Department of Economics and Statistics "Cognetti de Martiis", Università degli Studi di Torino, Italy*

HIGHLIGHTS

- Hurdle rates are crucial in energy modeling but their values are often unreliable.
- Hurdle rates evaluated according to the WACC and the available literature.
- Assessment of the transition's cost sensitivity to the hurdle rates reduction.
- Exploring the role of technology-specific hurdle rates in the energy transition.
- Green finance may help but it is not sufficient to drive the energy transition.

GRAPHICAL ABSTRACT



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ABSTRACT

Technology-specific hurdle rates significantly influence capital expenditures for deploying new technologies in the energy system, yet their definition in energy system optimization models often lacks a solid evaluation basis. This is crucial for providing relevant policy insights on clean finance investments. To address this gap, this paper introduces a framework for evaluating the impact of green finance measures on the future evolution of energy systems. Using the weighted average cost of capital methodology and recent literature, we robustly evaluate hurdle rates and explore their sensitivity by assessing the impact of reduced hurdle rates for green technologies on the cost of the energy transition through TEMOA-Italy. We differentiate hurdle rates for green and brown technologies to measure their potential to encourage low-carbon investments. The findings indicate that reducing hurdle rates for green technologies results in relatively low potential savings for the energy transition cost. Additionally, a 2÷3 % difference in hurdle rates is required to shift competitiveness from brown to green technologies, exceeding the realistic impact of green finance measures like the EU Taxonomy for Sustainable Activities (estimated at around 1 %). Therefore, green finance schemes should be combined with other strategic measures to fully support the energy transition.

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* Corresponding author.
E-mail address: matteo.nicoli@polito.it (M. Nicoli).

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Nomenclature

AC	Alternating Current
BEV	Battery Electric Vehicle
CCUS	Carbon Capture Utilization and Storage
DC	Direct Current
ESOM	Energy System Optimization Model
EUTSA	EU Taxonomy for Sustainable Activities
GHG	Greenhouse Gas
HR	Hurdle Rate
LPG	Liquified Petroleum Gas
LULUCF	Land Use, Land-Use Change and Forestry
O&M	Operation and Maintenance
SC	Sensitivity Coefficient
SDG	Sustainable Development Goal
TEMOA	Tools for Energy Modeling Optimization and Analysis
TIMES	The Integrated MARKAL-EFOM System
WACC	Weighted Average Cost of Capital

1. Introduction

Unlocking sustainable investments is crucial to successfully foster the energy transition. This is crucial for achieving the Sustainable Development Goals (SDGs) [1] and specifically the 7th SDG [2], as the use of energy is the main responsible of greenhouse gases (GHGs) emissions worldwide [3]. According to the International Energy Agency (IEA), global clean energy investments in 2030 should increase from the announced USD 3.0 trillion in 2030 to about USD 4.6 trillion to reach the net zero CO_2 emissions target in 2050 [4]. These figures make clear that the energy transition cannot be achieved only through public funds, as also stressed by the COP28 [5] and the European Commission [6]: finance has a key role in unlocking the potential of green investments. Several measures have been proposed to enhance sustainable finance. For instance, the obligation to report sustainability practices and environmental data was introduced in the European Union [7,8], in the United Kingdom [9], in the United States [10] and in China [11].

The climate risks associated with investment projects urged investors to measure and reward the environmental sustainability of new investments. In this regard, the EU Taxonomy for Sustainable Activities (EUTSA) regulation [12], put in force since July 2020, classifies economic activities as sustainable if they substantially contribute to one of the six environmental objectives of the Green Deal as laid down in Article 9 from [12]. These objectives include climate change adaptation, mitigation, and the transition to a circular economy. Climate-sustainable activities are less likely to incur climate-related risks; as a result, environmentally sustainable activities are safer than pollutant (or "brown") activities [13]. Both lending institutions and investors should take these risks into account when financing new investment projects (see [14,15]), rewarding not only the economic but also the environmental sustainability of investment projects. Recent works, such as [16,17], find that companies engaged in the green transition have either better returns or lower cost of capital than companies investing in brown activities.

During the last decade, investments in the power sector, for instance, have been progressively shifting from fossil fuel-based to renewable-based projects [18], with some differences concerning the cost allocation according to the nature of the project. Indeed, low-carbon projects (including renewable electricity generation plants) are typically highly capital- and low operational cost-intensive, while most of the cost of fossil energy is related to the fuel cost, with lower capital expenditures [19]. Thus, the cost of the transition to low emissions-energy systems significantly depends on the discount rates applied on capital loans (as discussed in [19] for electricity production and in [20] for hydrogen). Therefore, tools used to inform policymaking in energy planning should accurately account for the cost of loans, evaluating their impact and associated risks on the projected evolution of the system.

In this context, the effectiveness of financial policies can be suitably tested through energy system optimization models (ESOMs). Such tools provide the least-cost configuration of an energy system over a medium-to-long term time scale and under a set of constraints that define a so-called energy scenario [21]. The system is described through a technology database with several techno-economic parameters (e.g., efficiency, costs, capacity factors, lifetime, etc.). Discount rates are among the most important parameters for modeling the financing costs of a project. Two different discount rates are included in ESOMs: first, the social discount rate, which reflects the society's preferences; second, the technology-specific discount rates, also defined as "hurdle rates" (HRs). HRs are defined as the minimum return a company is willing to accept before starting the project itself, given its risk and the opportunity cost of forgoing other projects [22]. They are used to account for the interests paid on the capital expenses associated with an investment, which are typically covered over several years thanks to the cash flow generated by the installed facility. Thus, they are crucial to evaluate the net present value of an investment project or to discount future costs. ESOM frameworks, such as TIMES [23], TEMOA [24] and OSeMOSYS [25] take into account such aspect. Since these models are technologically explicit and integrated [3], choosing appropriate HRs is particularly important, especially in providing relevant policy insights related to clean finance investments. The need to include accurately calculated HRs in ESOMs is twofold. First, the EUTSA [12] aims to facilitate direct investments in line with the European Green Deal [26] objectives, according to eligibility and alignment criteria (from 2022 and 2023 on, respectively). In this regard, HRs are directly affected by the cost of financing. As a result, including appropriate HRs in ESOMs would enhance accuracy in reflecting the cost of financing. Secondly, the HRs used in ESOMs are usually based on "educated guesses", and the absence of discussions about such values is a notable concern within the ESOM community, as pointed out in several peer-reviewed papers and technical reports [27]. For example, most of the values used in the JRC-EU-TIMES [28], the ETSAP-TIAM models [29,30], and the TIAM-Grantham [31] are taken from third-party sources, usually without delving into the underlying implications or assumptions behind their selection.

The state of the art above points out gaps associated with the definition and use of HRs in ESOMs. Indeed, there is a lack of discussion about the values adopted and their implications on models results. To address these gaps, this paper proposes a novel framework to assess, using ESOMs, the impact of varying the cost of capital of energy technologies on the future system evolution. In particular, once HRs of technologies typically included in ESOMs are properly defined, a sensitivity analysis on HRs is performed to evaluate the effects on:

1. The energy transition costs towards net-zero emissions in 2050. This is done to assess to which extent the presence of supporting schemes can decrease the decarbonization costs.
2. The competition among technologies in scenarios without emissions constraints. This is done to assess whether HRs variations may imply a spontaneous transition.

The analysis is performed for the Italian energy system through the TEMOA-Italy model [32]. Italy was selected as the case study for its peculiar energy-economic features, which may affect the competition between brown and green investments. Among the others, the main peculiarities of the Italian energy system are: higher electricity prices compared to most of the other developed countries [33]; high fuels prices (mainly in the transport sector due to high excises [34]); higher availability of renewable resources (specifically solar), compared to other EU member states [35], and consequent potential deployment of more capital-intensive technologies with respect to the traditional ones.

The paper is structured as follows. Section 2 presents the adopted methodology for the HRs derivation, introduces the technology classification and the perturbation of the HRs. Section 3 discusses the obtained results and Section 4 concludes the work, also presenting the main policy implications, limitations and future perspectives. Appendix presents more details on the TEMOA-Italy model, improving the analysis transparency and reproducibility.

2. Methodology

Fig. 1 represents the computational flowchart used to evaluate HRs and explore sensitivity scenarios to assess their influence on the future evolution of the system. The role of HRs in ESOMs is discussed in Section 2.1, while the methodology adopted to define the technology specific HRs is presented in Section 2.2. Section 2.3 discusses the technology classification between "green" and "brown" options (necessary to select technologies to be incentivized through the HR reduction) and Section 2.4 presents how the HRs sensitivity was implemented.

2.1. Role of the hurdles rates in ESOMs

ESOMs minimize the total system cost, which is usually computed by aggregating the stream of annual costs occurring during the whole model time horizon. Such costs represent the total cost of energy supply in the system under analysis. In the TEMOA open-source modeling framework [24], that is adopted for this work, the total system cost (i.e., the objective function) C_{tot} is calculated as in Eq. 1 [36].

$$C_{tot}(M€) = C_{loans}(M€) + C_{fixed}(M€) + C_{variable}(M€) \tag{1}$$

As in most of the ESOMs, the total system cost includes:

- Total system investment costs C_{loans}, computed through the aggregation of investment costs occurring when each technology is installed. For each technology installation year, the contribution to C_{loans} is proportional to the newly installed capacity of that technology through its investment cost, a model parameter measured in units of currency per unit capacity (e.g., $\left(\frac{M€}{GW}\right)$ for power plants).
- Total system fixed C_{fixed} and variable $C_{variable}$ costs, computed through the aggregation of the fixed and variable annual costs of technologies (e.g., operation and maintenance costs). For each year of the model time horizon in which technology operates, the contribution to C_{fixed} is proportional to the resulting available capacity, while $C_{variable}$ is proportional to the technology activity (that is the technology production).

In the calculation of the objective function, all the contributions to C_{loans}, C_{fixed}, and $C_{variable}$ are discounted to the initial year of the model time horizon through the social discount rate (referred to as the global discount rate in TEMOA), under the assumption that investment costs are paid through loans. As a result, HRs are used to discount the contributions to C_{loans}. The detailed description of the TEMOA objective function terms is available at [36], while the role of the HRs is outlined below.

$$C_{loans,t,v}(M€) = IC_{t,v}\left(\frac{M€}{cap}\right) \cdot CAP_{t,v}(cap) \cdot LA_{t,v}(-) \tag{2}$$

$$LA_{t,v}(-) = \frac{HR_{t,v}(-)}{1-(1+HR_{t,v}(-))^{-LLN_{t,v}(y)}} \tag{3}$$

Considering a technology t, for which $CAP_{t,v}$ is the newly installed capacity (measured in unit capacity cap) in the vintage v (installation year of the technology [36]) at an investment cost $IC_{t,v}$, the discounted contribution $C_{loans,t,v}$ to C_{loans} is calculated as in Eq. 2 through the loan annualize model-calculated parameter $LA_{t,v}$. The latter is a discount factor automatically computed by the model that includes two technology-specific model parameters: the technology hurdle rate $HR_{t,v}$ and the lifetime loan process $LLN_{t,v}$, also referred to as loan rate and period in TEMOA, respectively, and computed as in Eq. 3. The loan period is used to define the loan term associated with capital investment in a specific technology: if not specified by the user, the model automatically assigns to it the technology's technical lifetime (another model parameter).

Hence, HRs in TEMOA are used to increase investment costs by increasing total capital recovery over the project's lifetime. Hence, the higher the HR, the higher the annual payments spread over the loan period, thereby increasing the total system costs, as shown in Eq. 2 and Eq. 3. [31]

Although C_{loans} is the only component of C_{tot} directly including HRs in its formulation, any perturbation of their values directly impacts the economic competition between alternative technologies and may indirectly result in a variation of the total C_{fixed} and $C_{variable}$ too. For this reason, all the cost components will be considered in the results analysis of this study.

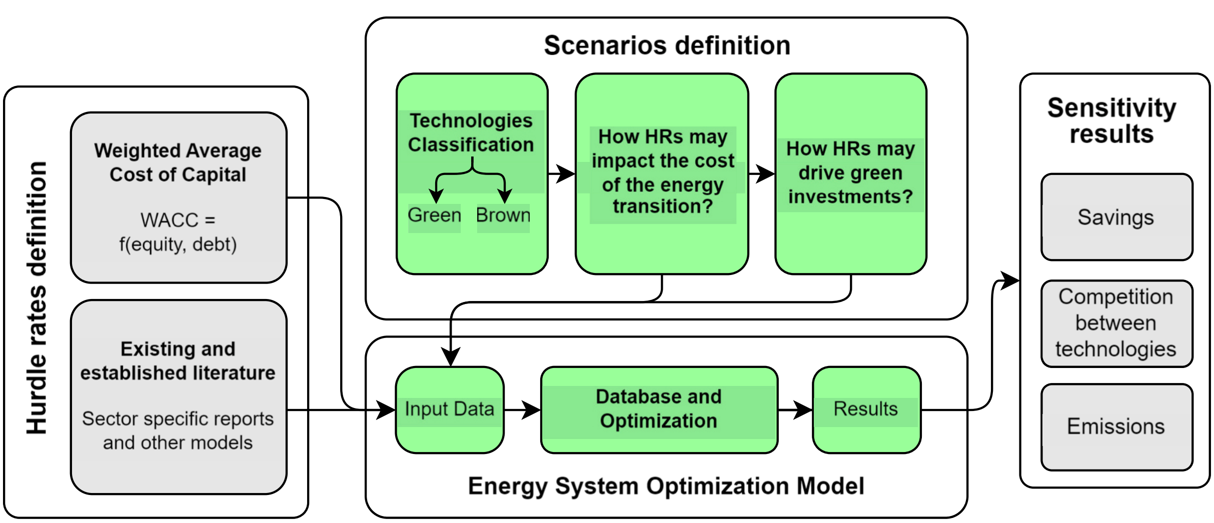

Fig. 1. Flowchart representing the methodology adopted to evaluate HRs and explore sensitivity scenarios to assess their influence on the cost of the energy transition and on driving green investments. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

2.2. Evaluation of the hurdle rates

Two strategies were adopted to find appropriate HRs for the technologies typically included in an ESOM instance.

First, the weighted average cost of capital (WACC) methodology was chosen as a reference. This well-established method to calculate discount factors is described in [37]. Second, in case of lack of the data needed to use the WACC definition, the existing literature was extensively studied to find evidence of adopted HRs (see the references listed in Table 1). The cost of capital is considered an effective indicator for assessing investment risks as it represents a weighted average of the cost suffered by a company to finance a project, given by equity and debt. Moreover, it has been widely used in the energy system modeling field (see, among others, [6,38]). WACC is calculated as a weighted average between the cost of debt and equity, that indirectly include risks associated with technologies investment, as reported in [22]. This methodology was used to compute the HRs for industry and fossil-based transport technologies (see Table 1).

Concerning electricity production options, due to the lack of some parameters involved in the cost of capital computation, process-specific values were adopted from an analysis conducted on WACCs in Italy in 2015 [39], as reported in Table 1. Moreover, the abovementioned parameters are usually taken from listed companies, and such values are not yet widely available for the hydrogen supply chain. Hence, HRs for hydrogen production technology were set equal to the assumption made in [40] (where global average HRs are provided): since that report only considers the production technologies, the value was also assumed for hydrogen storage and utility-scale fuel cells (see Table 1). Similar difficulties were encountered for hybrid, electric, and hydrogen vehicles. For this reason, assumptions based on the corresponding traditional technology options are proposed in Table 1. Specifically, the HR of electric trucks was assumed equal to 10 % - slightly higher with respect to internal combustion engine (ICE) vehicles - to represent the lower technology readiness level, and the HR of hydrogen vehicles was assumed equal to 15 % - significantly higher - to also consider the current absence of an infrastructure for hydrogen distribution for road transports in Italy [41]. Assuming higher HRs for electric and hydrogen vehicles is consistent with the approach proposed in [42], also considering the limited access to capital and the current lack of infrastructure for the spreading of hydrogen-based technologies. Concerning the HRs for hydrogen, ammonia, and methanol non-road transport systems (i.e., railways, aviation, and navigation) the values from the TIAM-Grantham model [42] were used (see Table 1).

2.3. Classification of technologies

Climate change risks should be taken into account when financing new investment projects. As a result, investors and lending institutions should face lower risks and then pay lower risk-premia associated with investments in technologies that contribute to climate change adaptation, mitigation, transition to circular economy and significantly reduce the amount of GHGs emissions. To capture the possible impact of green finance in promoting such technologies (and penalize brown technologies), the analysis of alternative HRs scenarios is carried out in order to identify possible thresholds leading to relevant variations in the model outcomes.

First, a classification of investment projects in TEMOA-Italy is carried out according to their emission levels, partially following the criteria beyond the EUTSA framework [12], as the cost of capital is expected to change for both green and brown investments due to climate risks and sustainable finance. *The TEMOA-Italy supply-side encompasses the upstream sector* [43]*, power and heat production* [44]*, and a detailed hydrogen module, as described in* [45]*. Moreover, carbon, capture, utilization, and storage (CCUS) options are also available (see* [46,47]*). Finally, agriculture, residential and commercial buildings, transport, and industry represent the demand-side* [48]*. The Release 3.1 of TEMOA-Italy* [49] *also includes an*

Table 1
Overview of the adopted HRs set and the associated source (WACC, external sources, assumptions).

Sector	*Sub-sector*	*Technology*	*Source*	*HR*
Power Sector	*Power Plants*	Coal and Oil	[39]	6.2 %
		Natural Gas	[39]	2.7 %
		Biomass	[39]	6.7 %
		Photovoltaic	[39]	5.7 %
		Onshore Wind	[39]	7.6 %
		Offshore Wind	[39]	8.6 %
		Geothermal	Assumption	5.2 %
		Hydroelectric	[39]	5.2 %
		Fuel Cell	[40]	8.0 %
	Storage	*Lithium-ion Batteries*	Assumption	8.0 %
Hydrogen	*Hydrogen Production*		[40]	8.0 %
		w/CCS	Assumption	10.0 %
	Storage	Tanks	Assumption	8.0 %
CCUS		*Synfuels Production*	*Assumption*	10.0 %
		Direct Air Capture	*Assumption*	10.0 %
Industry	Chemicals	High Value Chemicals	WACC	7.9 %
		Ammonia	WACC	10.0 %
		Methanol	WACC	9.2 %
		Chlorine	WACC	8.4 %
		w/CCS	Assumption	15.0 %
	Iron and Steel		WACC	9.5 %
		w/CCS	Assumption	15.0 %
	Non-ferrous Metals	Aluminum	WACC	7.4 %
		Copper	WACC	9.4 %
		Zinc	WACC	9.8 %
	Non-metallic Minerals	Cement, Lime, Ceramics	WACC	9.4 %
		Glass	WACC	6.5 %
		w/CCS	Assumption	15.0 %
	Pulp and Paper		WACC	9.9 %
Transport	Two Wheelers	ICEs	WACC	4.9 %
		Electric	Assumption	10.0 %
	Cars	ICEs, Hybrid, Electric	WACC	7.3 %
		Fuel Cell	Assumption	15.0 %
	Light Commercial Vehicles	ICEs, Hybrid, Electric	WACC	6.0 %
		Fuel Cell	Assumption	15.0 %
	Buses Medium Trucks Heavy Trucks	ICEs	WACC	6.0 %
		Electric	Assumption	10.0 %
		Fuel Cell	Assumption	15.0 %
	Rail	ICEs, Electric	WACC	4.2 %
		Fuel Cell	[31]	32.0 %
	Navigation	Traditional	WACC	5.8 %
		Innovative	[31]	32.0 %
	Aviation	Traditional	WACC	6.0 %
		Innovative	[31]	32.0 %

update set of HRs corresponding to the values presented in Table 1, for the power, hydrogen, CCUS, industry and transport sectors. The Appendix *presents the features of the TEMOA-Italy transport sector, with particular emphasis on the excises related to the energy commodities and the recharging cost of electric vehicles, together with the main features of the sector modeling structure. The use of the multi-sectorial and technology rich model, such as TEMOA-Italy, ensures a comprehensive analysis in terms of competition between technologies. This is crucial to derive relevant policy insights concerning the impacts of green finance on the future evolution of the complex and interconnected energy systems.*

The EUTSA is based on 6 sustainability criteria and applies to 14 economy sectors, establishing the eligibility of an investment in such sectors. Among the eligible investments, those aligned with the EUTSA comply with a technical screening to evaluate their alignment with a specific criterion, do not do significant harm to the other criteria, and comply with minimum safeguards [12]. Proper and comprehensive identification of the discriminating criteria is a complex issue and is behind this paper's scope (for a detailed discussion of how to inform energy policies with sustainability assessments, see [50]).

Since the only sustainability indicator, internally evaluated by TEMOA-Italy, is the GHG emissions associated with each technology [46], this work uses GHG emissions as a proxy for overall system sustainability. Therefore, it assumes that investments aimed at reducing emissions do not significantly harm other aspects of sustainability. Based on this, the technologies in the TEMOA-Italy model were classified as either green or brown by comparing their emission levels with sector-specific thresholds set by the EUTSA [12]. Technologies emitting below these thresholds were labeled as green, while those emitting above were labeled as brown. For example, the EUTSA sets a threshold of 100 g/kWh to differentiate between green and brown power plants [12]. Consequently, all fossil fuel-based plants in the TEMOA-Italy database are classified as brown, except for natural gas plants with carbon capture and storage (CCS), which emit around 40 g/kWh assuming a 90 % carbon capture rate [52] (see Table 2). Biofuel-based technologies are classified as green, as the CO2 emission factor for biofuels is assumed to be zero in TEMOA-Italy [46], along with other renewable energy sources. The distinction between green and brown technologies is important as it determines whether the investment is facilitated or penalized by the HRs variation from the reference values. More details about the classification of technologies and the adopted sector-specific thresholds can be found in [51], whereas an overview of the outcomes is provided in Table 2.

Table 2
Classification of green and brown technologies according to the emission thresholds.

Sector	*Sub-sector*	Technology	Classification
Power Sector	*Power Plants*	Coal and Oil Coal w/CCS Natural Gas Natural Gas w/ CCS	Brown
		Biomass Photovoltaic Onshore Wind Offshore Wind Geothermal Hydroelectric *Fuel Cell*	Green
Hydrogen	*Hydrogen Production*	From Fossil Fuels	Brown
		From Biofuels Electrolysis	Green
Industry			According to emission and efficiency thresholds detailed in [51].
Transport	Road	ICEs Hybrid	Brown
		Electric Fuel Cell	Green
	Rail	Electric Fuel Cell	Green
		Diesel	Brown
	Aviation	Kerosene	Brown
		Hydrogen	Green

2.4. Variation of the hurdle rates

Several recent works estimate a negative relation between the cost of debt and equity and climate change indexes, such as carbon emission intensity or compliance with sustainable goals. In particular, [53,54] focus on the cost of debt and find that this is positively related to emission intensity indexes, in a range between 12 and 43 basis points, depending on the estimation technique. This result means that, on average, EU firms bear a cost of debt financing from 12 to 43 basis points higher for each 100 basis points increase in carbon intensity. In [17,55], the analysis focuses on environmental sustainability and cost of equity, finding again a positive relation between the cost of equity and the lack of a firm's compliance with climate change targets. Estimates indicate that an increase in emission indicators (and lack of ESG compliance) generates up to a 0.92 % increase in the cost of equity. As a result, in our work, we consider 1 % as a plausible decrease for future variations in the cost of capital (i.e., in the HRs) associated with green projects. This estimate does not take into account variations in the share of equity or debt financing nor differences in β_L. Moreover, this value does not consider the differences between economic sectors or the possible changes in financing conditions that may happen in future years.

A sensitivity analysis should be carried out to evaluate possible changes in HRs and their impact on the switch to green technologies in pivotal sectors in the foreseeable future. Made those premises, the proposed HR reductions should not be considered as the realistic impact of possible green finance measures, but as explorative values having the mere purpose of testing the model sensitivity. This is done in order to identify possible thresholds in the HRs significantly perturbing the model outcomes, and to compare those thresholds with the realistically expectable HRs reduction due to better financing conditions for green projects (in the order of 1 % as abovementioned). In such a way, the adopted methodology for the HRs variation is suitable both to identify critical HR values in determining the cost of the energy transition (see Section 2.4.1) and the economic competitiveness between green and brown technologies (see Section 2.4.2).

2.4.1. Scenarios for the impact on the energy transition cost

The additional cost due to the transition is evaluated through the comparison of the total system cost for the Net0 scenario, which leads the system to net zero emissions in 2050, and the Base scenario, representing the system evolution without considering such decarbonization target (see Table 3). Then, the dependency of such additional cost on the HRs is examined by reducing the reference values (see Table 1) for the HRs of green technologies. This is done multiplying by a sensitivity coefficient (SC in Table 4) between 0.90 and 0.50, as reported in Table 3 and consistently with what done in [27]. Such a range is based on the

Table 3
List of the examined scenarios used to assess the impact of the HRs on the additional cost of the energy transition, their features concerning the HRs perturbation, the emission constraint application.

Scenario	Green Technologies	Brown Technologies	Emission Constraint
Base	Ref.	Ref.	No
Net0	Ref.	Ref.	Yes
Net0_**	Ref. × SC	Ref.	Yes

Table 4
List of the examined scenarios used to assess HRs levels driving a transition towards green investment, their features concerning the HRs perturbation, the emission constraint application.

Scenario	Green Technologies	Brown Technologies	Emission Constraint
Base	Ref.	Ref.	No
Green_**	Ref. × SC	Ref.	No
Brown_**	Ref. × SC	Ref. / SC	No

necessity of exploring a sufficiently broad interval for the HRs values to assess the model response. However, literature highlights that 1 % reduction of HR for green technologies are possible in the next years. The value suggested by the literature is included in our analysis.

Consider that the HRs of brown technologies are kept constant in the different scenarios. Indeed, since the energy transition is ensured by the presence of the emission constraint, studying scenarios with higher capital costs, which would be associated with a penalization of brown technologies, does not provide significant insights.

The specific emission constraint applied to TEMOA-Italy in the Net0 and Net0_** scenarios (see Table 3) represents a linear emission reduction trajectory starting from the 2020 emissions evaluated in the Base scenario and targeting 20 Mt. of residual emissions in 2050 (i.e., ~ 220 Mt. in 2030 and ~ 120 Mt. in 2040). Since the model does not include afforestation options and assuming that afforestation can guarantee enough negative emissions to compensate such a residual, this corresponds to net zero emissions. This assumption is supported by [56], estimating up to 45 Mt. the absorption potential due to Land Use, Land-Use Change and Forestry (LULUCF) in Italy. More details on the model structure are provided in Appendix.

2.4.2. *Scenarios driving green investments*

To evaluate whether the HRs variation may drive the transition to green investments in the different sectors, even without any emission target, other scenarios are investigated. Specifically, both the facilitation of green technologies (Green_** scenarios in Table 4) and the simultaneous penalization of brown options (Brown_** scenarios in Table 4) are explored. The penalization of brown technologies is justified by the increasing risks associated with such investments, for instance due to the possible introduction of restrictions to their installation or operation by law. See, for instance, the ban on sales of CO2-emitting cars and vans starting from 2035 recently approved by the European Parliament [57]. In the latter scenario group, HRs of brown technologies are divided by the same sensitivity coefficients used for green processes, varying again between 0.90 and 0.50.

3. Results and discussion

This section presents the HRs sensitivity analysis results obtained via TEMOA-Italy. First, we assess the impact on the transport sector of reducing the HR of green technologies in all the sectors. Second, we determine whether facilitating green investments over brown investments may drive a spontaneous transition. Finally, the implications on the energy transition cost (Section 3.1) and for boosting green investments (Section 3.2) are discussed.

The cumulative total and investments costs over the 2030–2050 period in the Base, Net0 and Net0_** scenarios are shown in Fig. 2. The lower cost of debt and equity in the Net0_** scenarios (due to the reduction of the HRs) implies a relevant reduction of the additional cost of the energy transition (evaluated as discussed in Section 2.4.1), in a linear fashion with respect to the reduction of the assigned HRs.

No relevant changes are deducible from Fig. 2 among the considered scenarios concerning the sectorial cost repartition and the cost sensitivity trend to the HR variation from the reference value (scenario Net0) to the lowest (scenario Net0_50), which is approximately linear. This is due to the fact that the optimal energy and technology mix associated with the Net0 and Net0_** scenarios are mostly driven by the presence of the emission limit (see Section 2.4.1) and unsensitive on the HRs, at least in first approximation and for the considered variation range. This outcome aligns with the findings of [27] for similar HRs variations and allows a fair cost comparison among the proposed scenarios.

The additional cost of the transition is computed as the relative difference between the costs associated with the Net0 and Net0_** scenarios and those relative to the Base scenario, over the 2030–2050 time interval. The outcome is shown in Fig. 2a and Fig. 2b for the total and the investment costs, respectively. The percentage cost increase due to the emission limit is higher for the investment costs (+ 27÷35 % compared to Base) than for the total costs (+ 14÷21 % compared to Base). This is due to a shift towards more capital and less operational cost intensive technologies allowing emissions reduction for traditional technology options. For instance, this is true for renewable-based power plants compared to fossil-fueled [52], for electric vehicles compared to the ICEs [58] and for heat pumps with respect to boilers.

As commented in Section 2.4, a realistic HRs reduction for green technologies (defined in this work as low emitting technologies) measures could be expected to be close to 1 %. Among the considered Net0_**, this corresponds to the Net0_90 one. Indeed, the average HR among those applied to the TEMOA-Italy technologies is 8.6 % and a 1 %

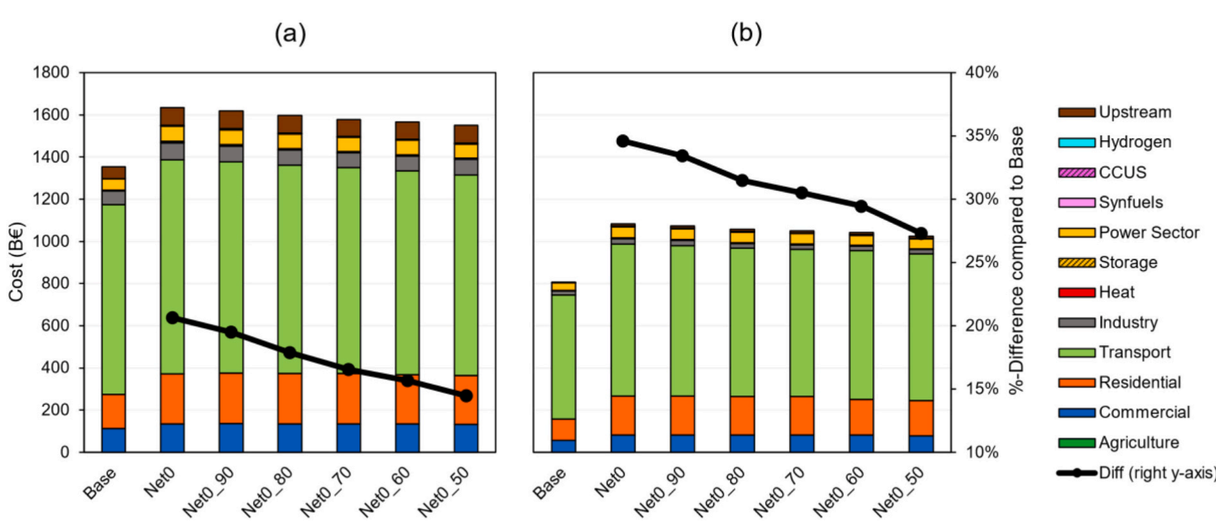

Fig. 2. Sectorial breakdown of the cumulative total system cost (a) and total investment costs (b) for the period 2030–2050 for the studied scenarios (Base, Net0 and Net0_**). The difference concerning the Base scenario (i.e., the energy transition cost) is also depicted.

cut leads to 7.6 % (i.e., 88 % of the reference value). Since the same outcome in terms of identification of the most representative scenario of green finance (the Net0_90) is associated with the average HR of the transport sector only, or the cars and heavy trucks sub-sectors (with 9.2 %, 7.6 % and 8.0 % as the average HR, respectively), the Net0_90 is the most realistic reduction step even at sub-sectorial level.

The effects of fostering the so-called green investments and discouraging brown ones in the absence of emissions reduction targets are assessed for the transport sector, which mostly contributes to the 2030–2050 cumulative total system (67 %) and total investment (73 %) costs in the Base scenario (see Fig. 2). The focus is on cars and trucks, since they represent the most capital-intensive sub-sectors, with 64 %

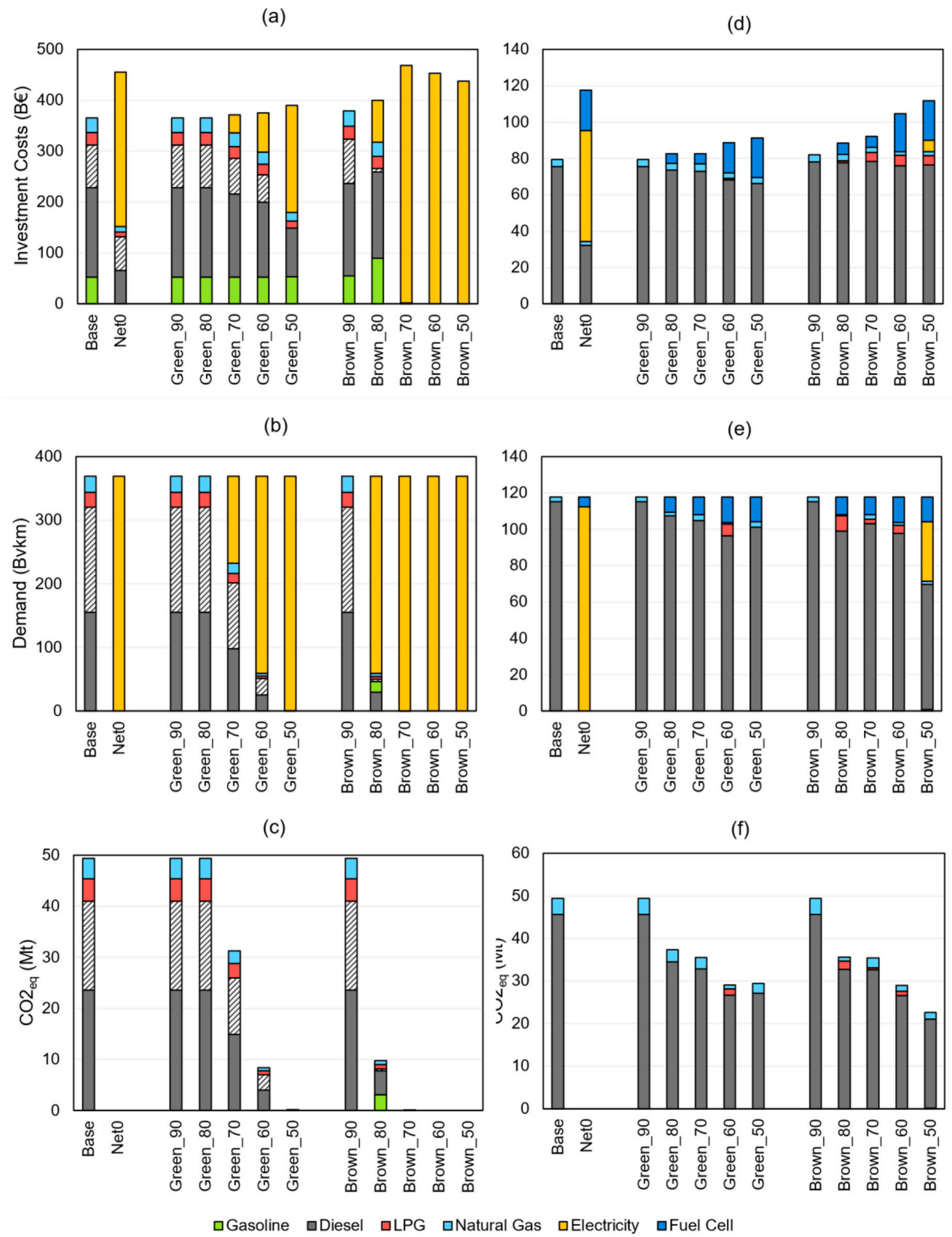

Fig. 3. Technological breakdown in the cars sub-sector for cumulative 2030–2050 total investment costs (a), 2050 fleet (b), and 2050 CO_2^{EQ} emissions (c) for the studied scenarios (Base, Net0, Green_**, and Brown_**). Trucks technological breakdown of cumulative 2030–2050 total investment costs (d), 2050 fleet (e), and 2050 CO_2^{EQ} emissions (f) for the studied scenarios (Base, Net0, Green_**, and Brown_**).

and 14 % of the total transport investments in the Base scenario, respectively (see Fig. 5a).

In the Base scenario only brown investments (according to Table 2) are reported in the period 2030–2050 (see Fig. 3a), also due to the excises modeling and the constraints set, as discussed in Appendix. With the mere reduction of the HRs of green technologies, electric cars are chosen by the model from Green_70 and reach the highest investments in Green_50, representing more than 50 % of the total investment costs for cars, especially at the expense of diesel and hybrid vehicles (the latter gasoline-fueled). Even though the BEVs investments are ∼30 % lower than in the Net0 scenario, halving their HRs allows them to satisfy almost 100 % of the 2050 demand, as shown in Fig. 3b (note that the investments in gasoline cars Fig. 3a refers to vehicles whose use ended prior to 2050).

3.1. Implications for the cost of the energy transition

The results of applying the HRs on the energy transition costs are shown in Table 5. It equals 279 B€ in the Net0 scenario (+ 21 % increase with respect to Base). Subsequently, the impact of the hurdle rates reduction is assessed as the difference of the transition cost between Net0 and Net0_90. Over the 2030–2050 period, this corresponds to a saving of 15 B€ when considering the realistic Net0_90 scenario and 84 B€ when considering the extreme Net0_50 scenario (halved HRs with respect to the reference values), as reported in Table 5. Expressed in savings per unit of relative HRs reduction with respect to the reference value (M€/%), the impact of the HRs reduction on the cost due to the energy transition is estimated at 11 M€/%. In percentage terms, the transition cost reduction due to the HR perturbation is estimated at 6 % for Net0_90 (and up to 30 % in the extreme Net0_50 scenario). Although there is evidence that lower HRs favor earlier investments in clean energy technologies [59,60], the average savings per unit of relative HRs reduction results quite low compared to the costs typically associated with the energy transition [61]. This is primarily due to the greater influence of strict emissions constraints on technological investments compared to the effects of HR reduction, leading to a decarbonized energy system already in the Net0 scenario. This suggests that while facilitating green investments may significantly contribute to reducing the cost of green investments, it may not play a transformative role when stringent emissions reduction targets must be met.

When considering the investment costs alone, the cost increase of the energy transition is similar in absolute terms but higher in percentage terms (+ 35 %), due to the transition towards more capital-intensive technologies when decarbonizing the energy system (see Table 5). Moreover, since HRs impact the investment costs only, the different sensitivity of total and investment costs on the HRs is due to a concurrent variation in the fixed and variable O&M costs of the involved technologies. Specifically, the reduction of the cost of loans in the Net0_** scenarios with respect to Net0 implies a reduction in the O&M costs too, due to investment in green technologies with lower operational

Table 5
Total and investment costs in the 2030–2050 time interval, cost of the energy transition and savings due to the HR reduction.

	Scenario	Cost (B€)	Transition Cost (B€) (from Base to Net0 and Net0_**)	Savings (B€) (from Net0 to Net0_**)
Total Costs	Base	1354		
	Net0	1634	279	
	Net0_90	1618	264	15
	Net0_50	1550	196	84
Investment Costs	Base	805		
	Net0	1083	278	
	Net0_90	1074	269	9
	Net0_50	1025	220	59

expenditures boosted. However, since the main driver for the technology selection in the Net0_** scenarios is the presence of the emission constraint (see Table 3), the savings associated with O&M costs equal 25 B€ in the extreme Net0_50 scenario, significantly lower than savings in investment costs for the same scenario (59 B€, as reported in Table 5).

In the Base scenario, the transport sector is the main contributor to the total investment costs, followed by residential, commercial, electricity production, and industrial sectors, while the others involve much lower cost fractions (see Fig. 2b). Moreover, these sectors experience, in the same order, the highest absolute investment cost increase due to the transition (from Base to Net0), with different trends about the additional total investment costs when decreasing the HRs, as represented in Fig. 4.

In particular, the transport sector shows the highest cost reduction (∼ 8 B€) from Net0 to Net0_90 and a slight increase in investment costs from Net0_70 to Net0_60 (see Table 6). Focusing on the specific technologies of the sector, this behavior is mainly due to electric car investments being anticipated in 2030 thanks to the HR reduction, with a consequent increase in transport investment costs. The technology competition within the transport sector is assessed in more detail in Section 3.2 for the Green_** and Brown_** scenarios. Much lower savings are computed for industry and power sectors, with ∼5 B€ in the extreme Net0_50 scenario with respect to the Net0 one. Residential and commercial sectors also show relevant transition cost decreases as an indirect consequence of the investment changes in the other sectors, since the HRs variation does not involve residential and commercial technologies, as discussed in Section 2.2.

Focusing on the three sectors interested by the HRs variation (see Table 1), Fig. 5 shows the sub-sectorial breakdown of transport, power sector and industry. The higher investments are related to the transport sector in all scenarios, while the power sector presents the highest relative increase in the investment costs. The power sector technology mix does not significantly vary with the HRs, being mainly driven by the emissions reduction constraint. No significant variations emerge in the sub-sectorial shares of the investments across the different Net0_** scenarios (associated with the HRs reduction). Concerning the cost of the transition from Base to Net0 and Net0_**, an approximately linear dependency on the HRs is highlighted for the power sector and the industry, while the transport curve shows a peak for Net0_60. As mentioned above, this is due to the anticipation of investments in electric cars to 2030 in such a scenario.

The cumulative investment costs in the power sector are mainly devoted to renewable energy sources (in all the scenarios, see Fig. 5b), where they account for around 80 % of the total (66 % of which including solar and wind), since the inclusion of the EU Emission Trading System discourages fossil fuels investments [62]. Being renewable potentials saturated in all the Net0_** scenarios, the higher

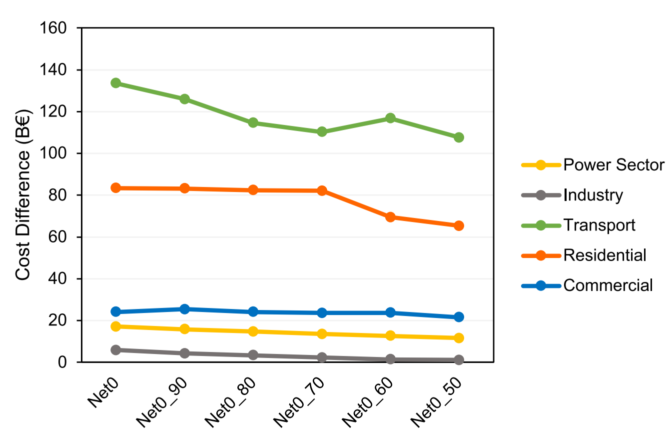

Fig. 4. Sectorial breakdown of the additional total investment costs due to the transition by Net0 and Net0_** scenarios. Cumulative costs for the 2030–2050 period are depicted.

Table 6
Sectorial investment costs of the transport sector, power sector and industry in the 2030–2050 time interval, cost of the energy transition and savings due to the HR reduction.

	Scenario	Cost (B€)	Transition Cost (B€) (from Base to Net0 and Net0_**)	Savings (B€) (from Net0 to Net0_**)
Transport	Base	588		
	Net0	721	134	
	Net0_90	713	126	8
	Net0_50	695	108	26
Power Sector	Base	36		
	Net0	53	17	
	Net0_90	52	16	1
	Net0_50	47	12	6
Industry	Base	20		
	Net0	26	6	
	Net0_90	24	4	2
	Net0_50	21	1	5

electrification of the end-uses in the latter implies a slight increase in the natural gas investments (~ 1 B€ increase in the Net0_50 compared to Net0). Further investments in the natural gas capacity are required to meet the reserve margin constraint [44]. On these bases, more to potential cost savings associated with lower HRs could be found by considering other constraints for the renewable resources than those currently included in TEMOA-Italy.

The slopes associated with the linear regressions of the lines shown in Fig. 5 allow to quantitatively compare the sensitivity of the additional sectorial costs due to the transition from Base to Net0 and Net0_** to the relative HRs reduction with respect to the reference value. A similar sensitivity resulted for the industry and the power sector (~ 1 M€/%), while the transport sector resulted to be the most sensitive (~ 5 M€/%). This result underlines the crucial role of capital expenditures in determining the feasibility of the ecological transition in the transport sector. Significant investments are required both for the vehicle fleet and the recharging infrastructure, as highlighted by [63] for the UK.

3.2. *Implications for boosting green investments: Green and brown scenarios*

The results shown in Fig. 3 point out the potential effectiveness of a HRs reduction in decarbonizing the cars fleet, with less than 10 Mt. of CO_2^{EQ} emissions when HRs of BEVs are reduced by 40 % and a complete decarbonization when they are halved (see Fig. 3c). This corresponds to approximately 2÷3 % of HR difference between electric and ICE cars, which is significantly higher than 1 % due to realistic green finance measures (see Section 2.4). Thus, a combination of such measures with complementary policies is necessary to effectively drive this sector towards the energy transition.

The penalty for brown technologies HR anticipates the penetration of electric cars already starting from Brown_80. Moreover, the contemporary premiums for green and penalties for brown investments, allow to almost end investments in ICEs in the period 2030–2050, as shown in Fig. 3a: that is in line with the EU ban on sales of CO2-emitting cars and vans starting from 2035 [57]. Again, this corresponds to a HR difference between electric and ICE cars around 2÷3 %, supporting the abovementioned results for the value implying a spontaneous transition to BEVs in the cars sub-sector. The confirmation of this outcome even for the Brown_** scenarios suggests that the 2÷3 % threshold makes the costs for the traveled kilometer by BEVs cheaper than those traveled by ICEs, independently on how this difference is achieved. These costs include capital and lifecycle expenditures, as discussed in Section 2.1. However, the spontaneous and complete transition associated with scenarios from Brown_80 onwards is achieved by considering an increase in the HRs of ICE vehicles, which would raise their total costs of ownership during the transition phase.

Concerning the trucks, the perturbation of the HRs in the Green_** and Brown_** scenarios is not sufficient to change the technology competition between ICEs, electric and fuel cell vehicles. Indeed, diesel trucks represent the highest share both in terms of investments and traveled kilometers (see Fig. 3d and Fig. 3e). Fuel cell trucks start to enter the vehicles mix in the Green_90 scenario, which is representative of the realistic HR reduction due to possible green finance measures, as discussed in Section 2.4. However, hydrogen vehicles represent a low share of the fleet in the Green_** scenarios, and they are competitive only in the heavy-duty sub-sector. In the extreme Green_50 scenario (HRs halved), the investments in fuel cell trucks approximately equal the ICEs ones, with hydrogen heavy trucks satisfying only 12 % of the total freight transport demand in 2050. On the contrary, BEVs result to be not competitive in the road freight transport in the Green_** scenarios.

The concurrent HRs decrease and increase of green and brown technologies, respectively, implies higher investments along the Brown_** scenarios than the Green_** ones and facilitate investments in hydrogen and electric trucks. Indeed, while the results for the Brown_90 to Brown_60 scenarios are comparable to the Green_** ones, in the extreme Brown_50 scenario, BEVs investments appear within the light and medium duty. In such a scenario, electric vehicles satisfy almost one third of the trucks demand in 2050 (see Fig. 3e), allowing halving CO_2^{EQ} emissions compared to the Base scenario (see Fig. 3f). However, these numbers are much lower than in the Net0 scenario, where a full decarbonization of the trucks fleet is possible in 2050, since electric and fuel cells vehicles satisfy, respectively, 95 % and 5 % of the demand, as depicted in Fig. 3e.

The results highlighted for heavy and medium/light trucks suggest the adoption of differentiated policies for the different freight transport size categories, as the optimal pathway to be followed may not be the same. Moreover, concerning the penetration of fuel cell hydrogen heavy trucks, it should be considered that this implies a development of the hydrogen supply chain and delivery infrastructure. In this regard, the introduction of combined facilitations for the deployment of hydrogen production technologies could make the transition to fuel cell vehicles easier.

4. Conclusions

This paper proposes a robust methodology to evaluate hurdle rates (HRs) for a wide range of ESOM technologies and to analyze the sensitivity of the results to variations in these rates. The methodology is based on the WACC formula where data are available, and on existing literature where data are absent. The analysis aims to study both the impact of HRs on the cost of the energy transition and the economic competitiveness between green and brown technologies.

The different assumptions on the HRs resulted in a minor impact on the total costs of the system in the presence of an emission constraint driving the decarbonization. When considering only the investment costs, their sensitivity on the HRs is higher and the additional cost due to the transition varies in the range + 27÷35 % compared to the costs associated with the Base scenario. However, the selected technologies in the Net0_** scenarios do not significantly vary, as the selection is primarily driven by the emission constraint. The transport sector incurs the highest investment costs compared to the other sectors, and it is associated with the greatest savings due to the HRs perturbation. Specifically, for the Italian case study, around 8B€ could be saved through the introduction of policy measures that facilitate green investments, resulting in a 1 % reduction in the HR relative to the reference values.

On the other hand, unconstrained scenarios allowed for the identification of critical threshold in HRs that produce significant changes in the technological choices of the model. Focusing on the transport sector and on cars specifically, a threshold of 2÷3 % difference in the HRs for

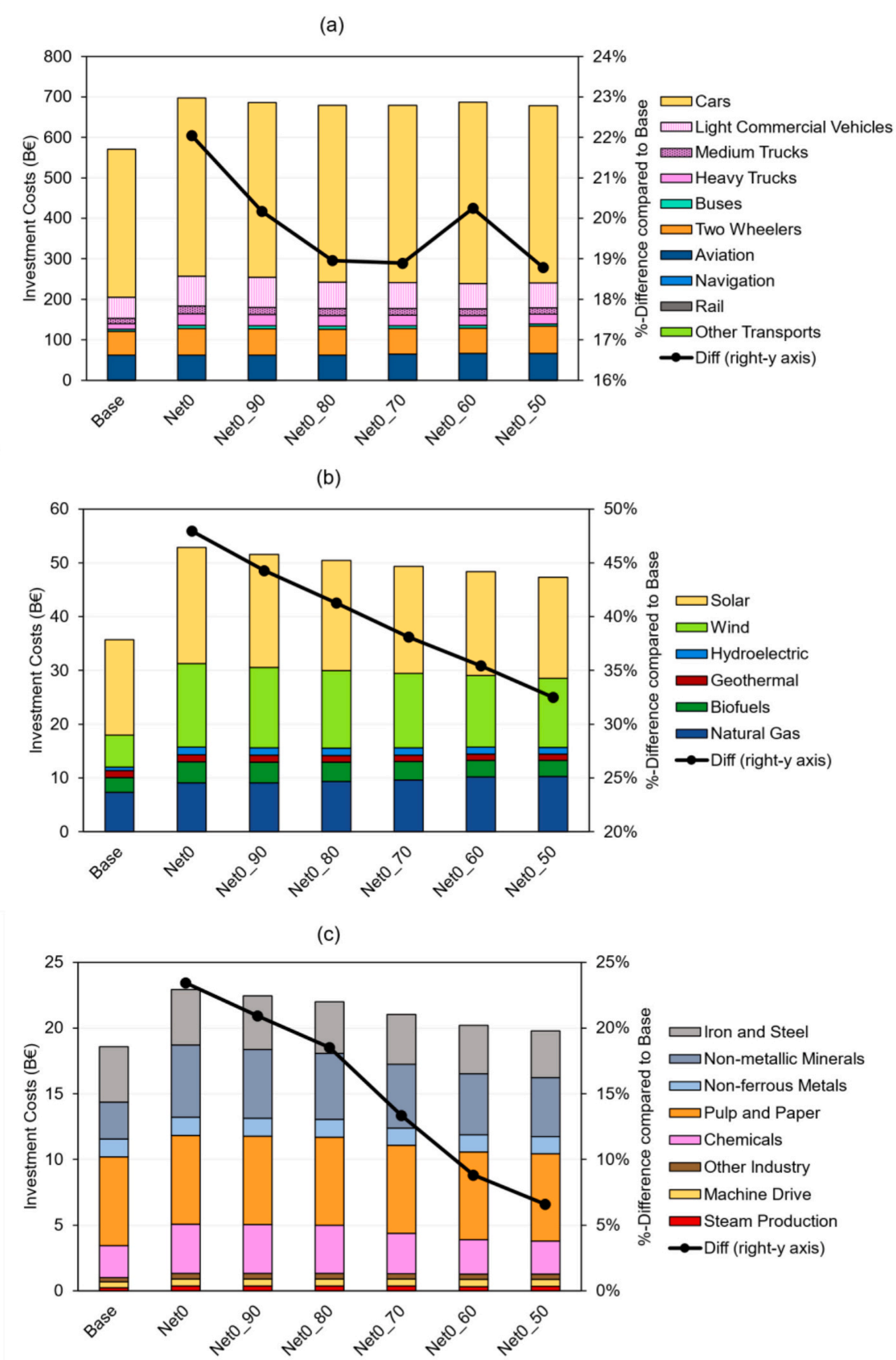

Fig. 5. Sub-sectorial/technological breakdown of 2030–2050 cumulative total investment costs for the (a) transport, (b) power, and (c) industry sectors by studied scenario (Base and Net0). The difference (Diff) with respect to the Base scenario (i.e., the energy transition cost) is depicted too.

ICEs and electric cars has been identified as pivotal in determining the competitiveness of electric vehicles over the traditional ones. This is verified both for Green_** scenarios (only considering a reduction in the HRs of electric cars) and Brown_** scenarios (also applying an increase in the HRs of traditional cars). However, these values are significantly higher than the 1 % reduction which is expected to be associated with possible green finance measures.

Using the CO_2 content of various technologies as an indicator of their green or brown status, we find that the financial framework introduced by the EUTSA does not result to be effective in driving the transition to green investments if not combined with other policies. However, decision-makers should consider that policies aimed at changing the HRs are insufficient to drive the energy transition towards a decarbonized economy. Other policies, such as carbon pricing, subsidies to renewables and incentive to green investments should be kept in place. For the EU specific example, more integrated fiscal rules may also help in reducing the risks associated with policies' decentralization and, consequently, discount rates, as suggested by [64].

Three main limitations are identified. Firstly, the unavailability of reliable data to compute the HRs for some innovative technologies requires the use of devoted assumptions, which inevitably introduces further uncertainties into the study. Secondly, the results may be significantly dependent on the specificities of the Italian case study. Indeed, the presence of higher excise levels for energy commodities and electricity prices compared with most of the other comparable countries may influence the results and affect their general validity. Finally, the proposed classification between green and brown technologies is only based on their emission factors. Such a choice may not be adequate to represent green finance policies expected to consider a broader sustainability criterion.

In perspective, the adopted HRs definition could be extended to consider sectors out of the scope of this paper (e.g., residential, commercial, agriculture). The assumptions due to the lack of data (e.g., fuel cells and electric vehicles, CCUS technology, etc.) could be made more reliable by considering other data sources, if available. Additionally, the scope and the relevance of the analysis could be extended by considering other countries. Finally, the adopted classification of green and brown technologies could be revised by considering, for instance, other sustainability criteria included in the EUTSA rather than the mere GHGs emissions.

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CRediT authorship contribution statement

Matteo Nicoli: Writing – original draft, Visualization, Validation, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Gianvito Colucci:** Writing – original draft, Visualization, Validation, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Valeria Di Cosmo:** Writing – review & editing, Writing – original draft, Methodology, Formal analysis, Conceptualization. **Daniele Lerede:** Conceptualization. **Laura Savoldi:** Writing – review & editing, Supervision, Funding acquisition, Conceptualization.

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.

Data availability

The complete set of outputs related to this work is available in the supplementary material. The release 3.1 of TEMOA-Italy is available at [49]. The release 1.0 of the MAHTEP version of TEMOA is available at [65].

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Appendix A

The methodology presented in this work is applied to the TEMOA-Italy model [18,66]. Its technology-rich database, in the version used for this paper, is available at [49] and includes several technologies within the multi-sectorial energy system. More specifically, the techno-economic modeling of transport sector technologies was revised and improved for the purposes of this work. For this reason and given that the transport sector is responsible for most of the system investment costs (as discussed in Section 3.1), which are the cost component directly influenced by the HRs (see Eq. 2 and Eq. 3), the main features of the model transport sector are presented in the following.

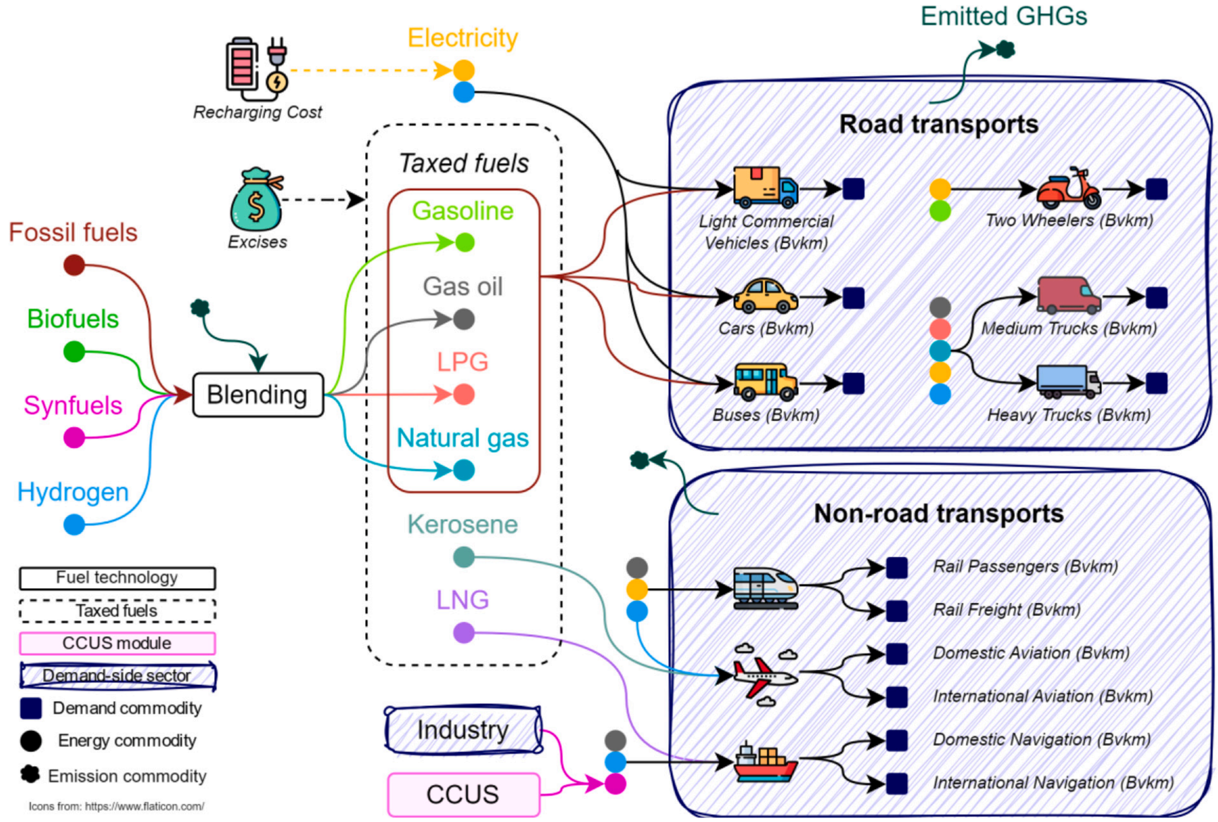

Fig. A1. Scheme of the TEMOA-Italy transport sector. The input emission commodity to the blending represents negative emissions associated with biofuels and hydrogen, according to the emissions accounting methodology discussed in [46].

The TEMOA-Italy transport sector comprises the road, rail, aviation, and navigation transport sectors, as shown in Fig. A1. Each one of these sectors includes several sub-sectors, associated with specific final transport demands. The road category includes two wheelers, cars, and buses for passengers' transport, together with light commercial vehicles, medium trucks, and heavy trucks for freight transport. Trasport by railways is divided into passenger and freight transport, while aviation and navigation are both detailed in domestic and international trips. Two final demands are devoted to representing other transports concerning the abovementioned and non-energy uses of energy commodities in the transport sector (e.g., lubricants), corresponding to the structure adopted by the Eurostat Energy Balances [67].

Fig. A1 shows the final energy consumption mix for the transport sector in Italy in 2006 (the TEMOA-Italy base year) and 2021 (the last year of the model calibration), taken from [67]. It should be observed that the transport sector strongly relies on fossil fuels and, specifically, on oil product consumption. Indeed, diesel fuel, gasoline, LPG, and kerosene account for 90 % of the energy consumption for transports in 2021 [67]. A slightly increasing share in the transport fuel mix from 2006 to 2021 is associated with LPG and natural gas consumption (helped by the lower excises compared to diesel fuel and gasoline [34]) and biofuels (blended with fossil fuels). Kerosene consumption is due to the aviation sub-sector, and electricity consumption is mostly due to rail transport.

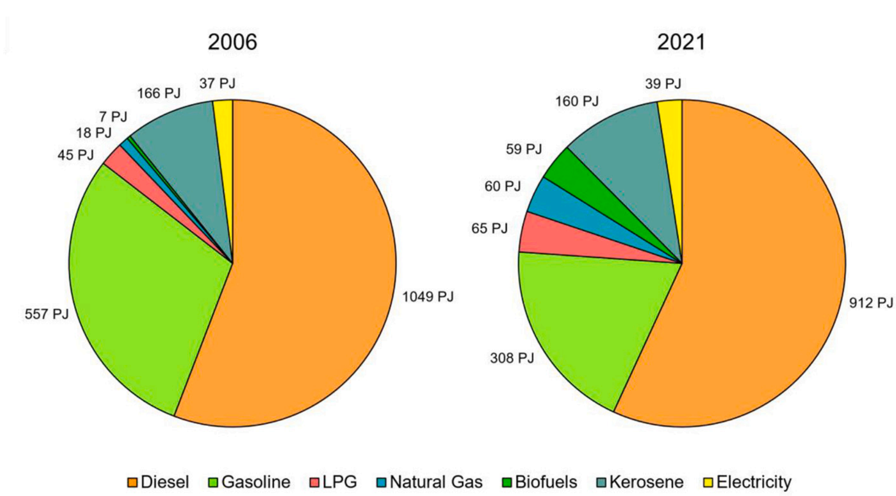

Fig. A2. The Italian transport sector final energy consumption in 2006 and in 2021, from [67].

While the complete techno-economic characterization of the existing and new technologies used in this work is open and accessible at [49], a focus on the modeling strategy adopted to represent key aspects in the economic competition between the alternative input energy commodity of the transport sector is provided here.

Focusing on the cars sub-sector (responsible for most of the final energy consumption, emissions and investment costs within the transport sector in the 2006–2021 period [67]), an overview of the techno-economic characterization of new technologies is provided by Table A1. While the characterization of diesel, gasoline, LPG and natural gas technologies in 2020 is based on [68], the exogenous technology learning (efficiency improvements and cost decrease) and the parameters for electric, full hybrid and fuel cell cars are estimated by applying the same proportionality factors provided by [28]. Parameters in Table 7 for 2022 were also double-checked with those provided in [69] for 2022 in Germany.

Table A1
Techno-economic characterization of competing new technologies belonging to the cars sub-sector of the TEMOA-Italy transport sector.

Cars New Technologies	*Lifetime*	*Efficiency (Bvkm/PJ)*		*Investment Cost (M€/Bvkm)*		*Fixed O&M Cost (M€/Bvkm)*
		2020	*2050*	*2020*	*2050*	
Diesel	*12*	*0.43*	*0.50*	*1730*		*63*
Gasoline	*12*	*0.36*	*0.42*	*1500*		*63*
LPG	*12*	*0.34*		*1530*		*64*
Natural Gas	*12*	*0.36*		*1620*		*64*
Battery Electric	*10*	*1.18*	*1.37*	*2540*	*1970*	*51*
Full Hybrid	*12*	*0.51*	*0.69*	*1830*	*1730*	*62*
Hydrogen Fuel Cell	*10*	*0.64*	*0.94*	*3770*	*2920*	*70*

Specifically, Italy imposes quite high excises on transport fuels compared with the other EU member states and the US [33]. Excises were implemented in the model as reported in Table A2, elaborated by *[34]* and correspond to the 2023 excise levels, which are assumed to be kept constant for future years. This assumption is consistent with the past evolution of the excises, which were kept constant in time by the Italian government, with the exceptions of the early 2010s European sovereign debt crisis and the 2022 energy prices crisis [70].

Considering the relevant difference in the excise levels between liquid oil products (gasoline and diesel fuels) and gaseous fuels (LPG and natural gas) in the transport sector, the mere economic competition would correspond to substituting diesel and gasoline vehicles in favor of gas-fueled vehicles. Since this behavior would be in contrast with the actual market shares (due to aspects not directly considered by the model such as the customer preferences, the different capillarity of the distribution network for the different fuels, etc.), specific constraints were introduced to reproduce the current (2020s [67]) fuels share within traditional vehicles in the cars and trucks sub-sectors. Such constraints assume internal combustion engine cars (gas oil, gasoline, LPG, and natural gas fueled) and full-hybrid cars as traditional vehicles [49] in competition, as a group, with "innovative vehicles" such battery electric and fuel cell ones.

Table A2
Excise levels for each energy commodity by end-uses as detailed in [34] (the association with the TEMOA-Italy sectors for the carburation and heating end-uses is reported in brackets).

Commodity	Carburation (Transport)	Industrial Uses	Electricity Production	Heating (Buildings)	Unit of Measurement
Gasoline	22.28				M€/PJ
Kerosene	10.09			10.09	
Diesel Fuel	16.36		0.34	10.68	
Heavy Fuel Oil		4.31	0.37	5.14	
LPG	5.81		0.02	4.12	
Coal		0.45	0.35	0.36	
Natural Gas	0.10	0.37	0.01	5.23	
Electricity	2.78	2.78		6.31	

Another relevant aspect included in the TEMOA-Italy transport sector economics concerns the cost of electric vehicle recharge. Indeed, ESOMs (and TEMOA-Italy, too) do not typically include a detailed modeling of electricity operational dispatching and the associated costs, focusing on long-term energy planning and investments and only accounting for operational aspects in a simplified way [71]. These issues are relevant, for instance, for the electric vehicle recharging process, occurring at higher prices than the average price of electricity (both for private and public charging points) [72].

To avoid neglecting the additional cost associated with the electric vehicle's recharge or vehicles recharging with respect to the average electricity price, such a cost component was exogenously implemented in the model as a variable O&M cost of electric vehicles (see Table A3). This accounts for the cost of the recharging infrastructure and for the cost component associated with the available power. The data involved in the computation are shown in Table A3, where the specific consumption is the reverse of the efficiency of electric vehicles as modelled in TEMOA-Italy [49] (the 2050 values are reported here as an example).

Table A3
Estimation of the power cost component for electric vehicles recharging process.

Technology	Specific Consumption	Cost of Recharge	Cost of Energy	Cost of Power	
	(kWh/100 km)	(€/kWh)	(€/kWh)	(€/kWh)	(M€/Bvkm)
Two Wheelers	6.88	0.31	0.22	0.09	6.04
Buses	161.50	0.54	0.22	0.32	513.26
Cars	20.29	0.31	0.22	0.09	17.82
Heavy Trucks	195.62	0.54	0.22	0.32	621.69
Light Commercial Vehicles	22.01	0.54	0.22	0.32	69.95
Medium Trucks	85.73	0.54	0.22	0.32	272.47

The average cost of recharge for Italy is taken from [72] and it represents the total cost of the recharge, assuming that the private price (0.31 €/kWh) well represents the average recharging price of two-wheelers and cars, and the public AC price (0.54 €/kWh) proper estimates that for buses and freight transport (the public DC price, also provided by [72] and equal to 0.68 €/kWh is not considered being a very high value). The cost of energy is the average household cost of electricity in Italy for the period 2010–2021, taken from [73]. Such a period was chosen to exclude the 2008 financial crisis and the 2022 energy crisis, while the average industrial cost (slightly lower and equal to 0.18 €/kWh) was not considered conservative in estimating the power cost component. Knowing the average cost of the recharge (Cost_R) per each vehicle and the average cost of energy (Cost_E), the cost of power (Cost_P) is estimated as the differences between them and converted from €/kWh to M€/Bvkm through Eq. A4, where E is the specific energy consumption as reported in Table A1.

$$\text{Cost}_\text{P}\left(\frac{\text{M€}}{\text{Bvkm}}\right) = \left(\text{Cost}_\text{R}\left(\frac{\text{€}}{\text{kWh}}\right) - \text{Cost}_\text{E}\left(\frac{\text{€}}{\text{kWh}}\right)\right) \bullet \text{E}\left(\frac{\text{kWh}}{100\text{km}}\right) \bullet 1000\left(\frac{\text{M}}{\text{B}}\right) \tag{A4}$$

Appendix B. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.apenergy.2024.124633.

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