Energy Proceedings
Vol 39, 2024
ISSN 2004-2965

Technology-Specific Hurdle Rates for Energy System Optimization Models

Silvia Laera[1], Gianvito Colucci[1*], Valeria Di Cosmo[2], Daniele Lerede[2], Matteo Nicoli[1], Laura Savoldi[1]

1 MAHTEP Group, Department of Energy "Galileo Ferraris", Politecnico di Torino, Turin, Italy
(*Corresponding Author: gianvito.colucci@polito.it)

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

ABSTRACT

This work presents a methodology to evaluate technology-specific hurdle rates for energy system optimization models. Hurdle rates are usually assumed through educated guesses by energy system modellers, while they are estimated here by adopting the weighted average cost of capital methodology where possible and collecting data from the available literature in the other cases. The methodology is applied to the TEMOA-Italy open-source model: first, the updated hurdle rates are compared to the original model values; then, the effects of such an update are deepened in a base scenario. The results suggest that hurdle rates do not significantly affect the optimal system configuration (and the competition between the alternative technologies), while they vary the computed discounted costs of the technologies selected by the model.

Keywords: Discount rates, Hurdle rates, Energy system optimisation models, TEMOA-Italy, EU Taxonomy

NOMENCLATURE

Abbreviations	
CCUS	Carbon capture utilisation and storage
CDS	Credit default spread
ESOM	Energy system optimisation model
EU	European Union
HR	Hurdle rate
IEA	International Energy Agency
MRP	Market risk premium
PS	Project-specific spread
RES	Reference energy system
RFR	Risk-free rate
WACC	Weighted average cost of capital
Symbols	
cap	Unit of capacity
GW	Gigawatt
M€	Millions of euros
t	Index for technology
v	Index for technology installation year
y	Years

1. INTRODUCTION

Unlocking sustainable investments is crucial to face the energy transition successfully. 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 [1]. In this regard, the effectiveness of energy policies can be suitably tested using energy system optimisation models (ESOMs) [2]: such tools provide the least-cost configuration of a Reference Energy System (RES) over a medium-to-long term time scale and under a set of constraints that define a so-called energy scenario. The RES is described through a technology database with several techno-economic parameters (e.g., efficiency, costs, etc.). Discount rates are among the most important parameters to model 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, known as hurdle rates (HRs). Our analysis focuses on the latter, which 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. Thus, HRs are crucial to evaluate the net present value of an investment project or actualize future costs. Such an evaluation is usually included in ESOM frameworks such as TIMES [3] and TEMOA [4]. Since these models are technologically explicit and integrated [3], choosing appropriate HRs is

---

This is a paper for 15th International Conference on Applied Energy (ICAE2023), Dec. 3-7, 2023, Doha, Qatar.

particularly important, especially in providing relevant policy insights related to clean finance investments.

The need to include in ESOMs accurately calculated HRs is twofold. First, the European Union (EU) commits to foster investment in sustainable sectors through more accessible financing conditions for the so-called "green" projects. The recently issued EU taxonomy explicitly states the eligible sectors and sets the criteria for new projects to access favourable financing conditions [5]. 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. Second, 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 [6]. For example, most of the values used in the JRC-EU-TIMES [7], the ETSAP-TIAM models [6], [8], and the TIAM-Grantham [9] are taken from third-party sources, usually without delving into the underlying implications or assumptions behind their selection. Only the TIAM-Grantham model [9] adopts HRs that explicitly include risks, but the methodology developed to calculate them is not completely clear. As a result, it is not easy to understand the methodology used to calculate these discount rates and to assess the impact of the discount rates on the final model results.

Therefore, this work is aimed at providing a methodology to properly define HRs for the technologies typically composing the RES of ESOMs, to overcome the mentioned limitations. In particular, both the weighted average cost of capital (WACC) method and the existing literature were considered in the analysis, as described in Section 2. Then, the found values were used to update the HRs previously adopted in the TEMOA-Italy open-source model [10], [11], and the effects of such change were explored in a base scenario in Section 3. Finally, Section 4 concludes the work and outlines possible future developments.

2. METHODOLOGY

The assumptions adopted to define technology-specific HRs are presented in Section 2.1, while the role of discount rates in ESOMs is discussed in Section 2.2. A brief description of the model to which the methodology is applied is then provided in Section 2.3.

2.1 The hurdle rates evaluation

Two strategies were adopted to find appropriate HRs for the technologies typically included in an ESOM instance. First, the WACC methodology was chosen as a reference. This well-established method to calculate discount factors is described extensively in [12]. Nonetheless, the existing literature was extensively studied to find evidence of adopted HRs, in case of lack of publicly available data.

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 modelling field (see, among others [6] and [13]). The calculation of the WACC is described by Eq. (1), where E is equity, D is debt, $\mathrm{R_e}$ is the cost of equity, $\mathrm{R_D}$ is the cost of debt, and CTR is the corporate tax rate.

$$\mathrm{WACC} = \mathrm{R_e}\,\frac{\mathrm{E}}{\mathrm{E+D}} + \mathrm{R_D}\,\frac{\mathrm{D}}{\mathrm{E+D}}(1-\mathrm{CTR}) \qquad (1)$$

The cost of equity is usually calculated as the sum between the country-specific risk-free rate (RFR) and the market risk premium (MRP), weighted for an appropriate measure of the risk (β_L) arising from the exposure of an investment to the general market movements, as described in [14]. Instead, the cost of debt is the sum of the risk-free rate (here considered at the European level and called $\mathrm{EU_{RFR}}$), the Italian 10-year credit default spread (CDS), and the project-specific spread (PS) [15]. Table *1* shows the main parameters used to compute $\mathrm{R_e}$ and $\mathrm{R_D}$, that are independent of the economic sub-sector. Concerning the other parameters involved in the WACC calculation, values for β_L have been taken from [16], while the debt and equity financing ratio has been taken from [17]. These values vary according to the economic sub-sector, referred to as "Sub-industry" in [16], and they are reported in Table 2.

Table 1 Parameters and related references used to compute cost of equity and cost of debt.

CTR	RfR	MRP	$\mathrm{EU_{RFR}}$	CDS
24.00% [18]	2.54% [19]	9.02% [20]	0.39% [21]	1.27% [22]

Hence, given the economic sub-sectors included in the above-cited sources, the adopted HRs for industry and fossil-based transport technologies were computed through the WACC methodology. Instead, for the other sectors usually modelled in ESOMs, the HRs were directly taken from the literature. As for the electricity production systems, due to the lack of data for β_L and the ratios involving E and D, process-specific values were adopted from an analysis conducted on WACCs in Italy in 2015 [23]. 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 were directly taken from [24]: since that report only considers the production technologies, the value was also assumed for hydrogen storage and utility-scale fuel cells. Similar difficulties were encountered for what concerns hybrid, electric, and hydrogen vehicles, for which the values from the TIAM-Grantham model [9] were chosen. In this regard, HRs for hydrogen, ammonia, and methanol non-road transport systems (i.e., railways, aviation, navigation) were assumed the same as the hydrogen vehicles.

Table 2 Parameters used to compute the weighted average cost of capital (WACC), by economic sub-sector. The geographical scope of values from [16] and [17] is the Western Europe.

Economic sub-sector	$\boldsymbol{\beta_L}$	$\mathbf{R_e}$	$\mathbf{R_D}$	$\mathbf{\frac{E}{E+D}}$	$\mathbf{\frac{D}{E+D}}$
Commodity chemicals	0.83	10.0%	1.7%	75.8%	24.2%
Diversified chemicals	1.13	12.7%	1.7%	69.0%	31.0%
Fertilisers and agricultural chemicals	1.05	12.0%	1.7%	81.5%	18.5%
Industrial gases	0.83	10.0%	1.7%	81.5%	18.5%
Construction materials	1.09	12.4%	1.7%	73.9%	26.1%
Metals & glass containers	0.65	8.4%	1.7%	73.9%	26.1%
Paper packaging + Paper products	1.13	12.7%	1.7%	75.2%	24.8%
Aluminium	0.82	9.9%	1.7%	71.2%	28.8%
Diversified metals & mining	1.18	13.2%	1.7%	71.2%	28.8%
Copper	1.12	12.6%	1.7%	71.2%	28.8%
Steel	1.34	14.6%	1.7%	61.5%	38.5%
Airlines	0.78	9.6%	1.7%	56.5%	43.5%
Marine	0.85	10.2%	1.7%	50.5%	49.5%
Truck manufactures	0.91	10.7%	1.7%	50.5%	49.5%
Automobile manufacturers	1.61	17.1%	1.7%	38.0%	62.0%
Motorcycle manufacturers	0.92	10.8%	1.7%	38.0%	62.0%
Railroads	0.75	9.3%	1.7%	36.7%	63.3%

2.2 The role of discount rates in ESOMs

The traditional objective function to be minimised in ESOMs is 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 modelling framework [4], that is adopted for this work, the total system cost (i.e., the objective function) C_{tot} is calculated as in Eq. (2) [25]:

$$C_{tot}[M€] = C_{loans}[M€] + C_{fixed}[M€] + C_{variable}[M€] \tag{2}$$

As in many ESOMs, the total system cost includes:

- Total system investment costs C_{loans}, computed aggregating the investment costs occurring when technologies are 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 aggregating the fixed and variable annual costs of technologies (e.g., operation and maintenance costs). For each year of the model time horizon in which a technology operates, the contribution to C_{fixed} is proportional to the resulting installed capacity, while $C_{variable}$ is proportional to the technology activity (that is how much a technology produces).

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 amortise the contributions to C_{loans}. The detailed description of the TEMOA objective function terms is available at [25], while the role of the HRs is outlined below.

Considering a technology t, for which $CAP_{t,v}$ is the newly installed capacity (measured in unit capacity cap) in the year v at an investment cost $IC_{t,v}$, the amortised contribution $C_{loans,t,v}$ to C_{loans} is calculated as in Eq. (3) through the loan annualise model-calculated parameter $LA_{t,v}$. The latter is an amortisation factor

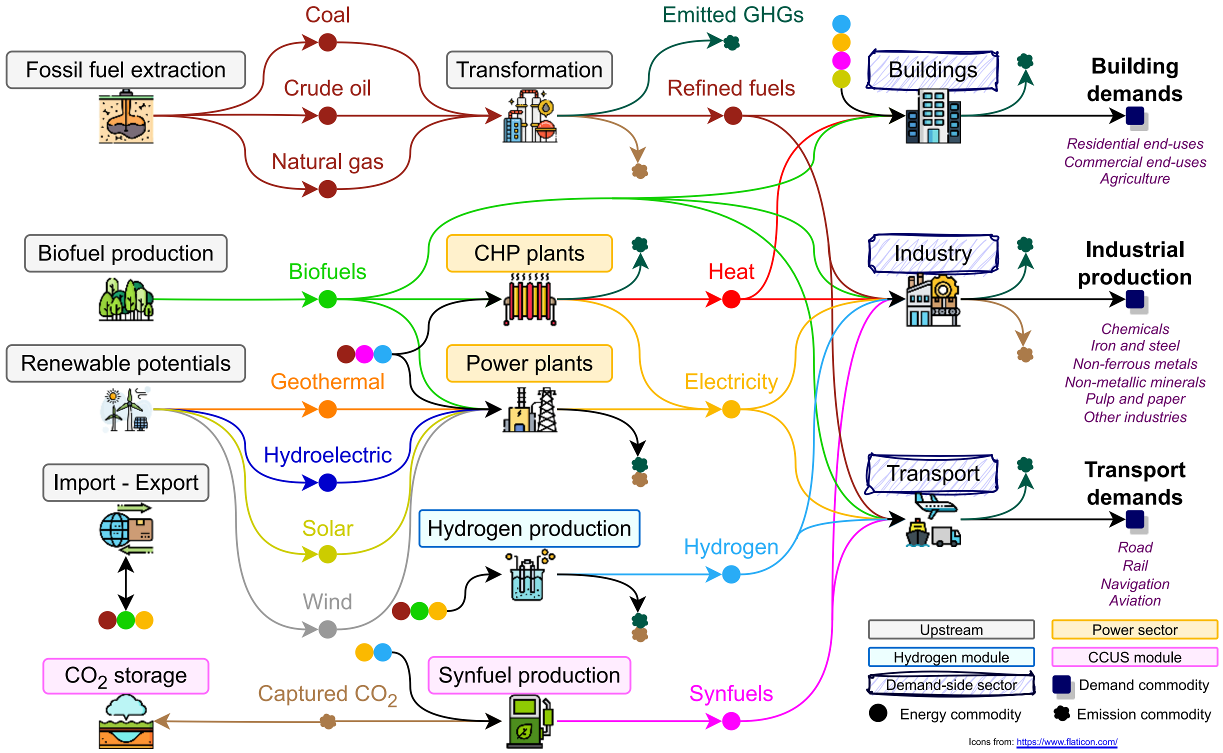

Fig. 1 Reference energy system of the TEMOA-Italy model [29]. The interconnection between the sectors is depicted through energy commodities and arrows, the latter representing the energy flow direction. Greenhouse gas (GHG) emissions and the Carbon Capture Utilization and Storage (CCUS) module are represented, too.

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 loan period in TEMOA, respectively, and computed as in Eq. (4). 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 technical lifetime, that is another model parameter. HRs in TEMOA are hence used to uplift the investment costs by increasing the total capital recovery over the project 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 Eqs. (3)-(4).

$$C_{\mathrm{loans},t,v}[\mathrm{M€}] = IC_{t,v}\left[\frac{\mathrm{M€}}{\mathrm{cap}}\right] \cdot CAP_{t,v}[\mathrm{cap}] \cdot LA_{t,v}[-] \quad (3)$$

$$LA_{t,v}[-] = \frac{HR_{t,v}[-]}{1-\left(1+HR_{t,v}[-]\right)^{-LLN_{t,v}[y]}} \quad (4)$$

2.3 The TEMOA-Italy model

The methodology presented in this work is applied to the TEMOA-Italy model [10], [11], which is based on the well-established TIMES-Italy model [26] (a benchmark between the two models is available at [10]). Its technology-rich database is fully accessible at [27] and includes many technologies that are integrated within the multi-sectorial RES pictured in Fig. 1. The upstream sector provides for the domestic production of fossil fuels and their subsequent transformation, as well as the renewable potential. Moreover, the model also accounts for the trade-off between fossil fuels, biofuels, and electricity. Then, the supply side also encompasses the power sector and hydrogen production [28], while the carbon capture utilisation and storage (CCUS) is modelled, too [29] [30]. Finally, agriculture, residential and commercial buildings, transport and industry [31] represent the TEMOA Italy demand modules. A comprehensive description of the implementation of the methodology presented here to TEMOA-Italy is available in [32].

3. RESULTS AND DISCUSSION

The calculation of HRs in TEMOA-Italy based on the well-established WACC methodology described in Section 2.1 represent a novelty compared to the traditional evaluation in other ESOMs. Results are first

Table 3 Comparison of the original TEMOA-Italy [27] hurdle rates set with the updated values, by energy sector and technology group.

Sector	Sub-sectors/technologies	Source	Previous value	Updated value
Power sector	Coal power plants	[23]	10.0%	6.2%
	Natural gas power plants	[23]	10.0%	2.7%
	Biomass power plants	[23]	5.0% ~ 10.0%	6.7%
	Solar PV systems	[23]	5.0%	5.7%
	Wind onshore turbines	[23]	5.0%	7.6%
	Wind offshore turbines	[23]	5.0%	8.6%
	Geothermal power plants	[23]	5.0%	10.0%
	Hydropower	[23]	5.0%	5.2%
	Decentralised cogeneration plants	[23]	5.0%	10.0%
Hydrogen value chain	All production modes (excluding systems with CCS), storage, utility scale fuel cell	[24]	5.0%	8.0%
CCUS	Synfuel production	Assumption	5.0%	10.0%
	Industrial processes with CCS	Assumption	30.0%	15.0%
Industry	Chemicals	WACC	30.0%	7.9% ~ 10%
	Non-metallic minerals	WACC	30.0%	6.5% ~ 9.5%
	Pulp and paper	WACC	30.0%	9.9%
	Non-ferrous metals	WACC	30.0%	7.4% ~ 9.4%
	Iron and steel	WACC	30.0%	9.5%
Transport	Internal combustion engine cars	WACC	10.0%	7.3%
	Hybrid and battery-electric transport systems (road and rail)	[9]	20.0%	24.0%
	Internal combustion engine trucks, light commercial vehicles, buses	WACC	10.0%	6.0%
	Two-wheel fossil-based vehicles	WACC	15.0%	4.9%
	Fossil based transport: rail, aviation, navigation	WACC	5.0%	4.2%, 6.0%, 5.8%
	H2, ammonia and methanol-based transport	[9]	5%, 10%	32%

presented by comparing HRs adopted through the presented methodology with the values previously used in TEMOA-Italy in Section 3.1. Moreover, the effects of such an update on the model results are described in Section 3.2. Moreover, all the updated values and the adopted sources are fully and freely accessible, as well as the entire model, allowing for easier third-party verification and comparison with other works.

3.1 The updated hurdle rates in TEMOA-Italy

The methodology presented in this work consisted of the update of the technology-specific HRs previously used in TEMOA-Italy [27]: the latter were taken from the TIMES-Italy model [26], when data were available, while a default value of 5% was assigned if no value was specified by the user [4]. Such an update involved the whole RES shown in Fig. *1*. Table *3* lists the differences between the values before (referred to as "*Previous value*" in the table) and after the analysis proposed in this work (referred to as "*Updated value*" in the table). Regarding the supply side, HRs from the literature were adopted for the power sector and the hydrogen module, as discussed in Section 2.1. In particular, the values of fossil-based power plants significantly decreased while the renewable ones increased, especially for wind and geothermal systems.

Overall, the HRs associated to power sector technologies are in line with other TIMES models [6], [7], [9]. Instead, the upstream sector has not been considered since appropriate values were not found. Then, the already used HR of 10% for power production technologies with CO_2 sequestration was also applied to the synfuel production processes included in the CCUS module. In this regard, the values for industry processes equipped with CO_2 sequestration were assumed at 15%, which is higher than the industry sub-sector values presented in Section 2.1. The only demand sectors involved in the update were industry and transport, for which the updated HRs significantly differ from the older ones. For all the industry sub-sectors, the HRs calculated with the WACC methodology are significantly lower than the rates included originally in TEMOA-Italy: from the initial 30%, they decreased down to the interval 6-10%, that is closer to the values of other TIMES models [9], [7]. This means that investments in the long run for these sub-sectors are more profitable than in the older TEMOA-Italy version. A smaller, but still significant change also occurred for the transport sector: in particular, there was an increase in the difference between the HRs of traditional fossil-based transports (whose values were more similar to the ones assumed in [8] and [9]) and the innovative and less pollutant solutions based on electricity and hydrogen.

3.2 Application of the new hurdle rates in TEMOA-Italy

This section presents the results of applying the HRs as reported in Table *3*. Two different scenarios were considered: scenario 1 includes the model original HRs, while scenario 2 the updated values. To avoid exogenously constraining the model, the studied scenarios do not include any emission limit or other exogenous targets.

In this context, summary results will be presented focusing on the power, transport, and industry sectors. Concerning the power sector, Fig. 2 shows the resulting electricity mix in 2050. No significant variations emerge by comparing the two scenarios in 2050, as well as for the previous year in the time horizon and for the available capacity of power sector technologies. This is expected, since the updated HRs do not vary substantially from the old values. The presence of renewables (mainly solar) in the electricity mix, even in scenarios without any decarbonisation constraint, is due to constraints on the technology mix for future years based on the 2020 system configuration.

A similar behavior is highlighted by the comparison of the final energy consumption breakdown by energy commodity for the demand-side sectors (i.e., buildings, industry, and transport). Given the relevant variation in the HRs for most of the model sectors (see Table *3*), the results suggest that the HRs play a minor role in determining the economic competitiveness of a technology option. This is also confirmed by more detailed results presented in [32]. The low sensitivity of model results to the HRs is more extensively discussed in [32] and confirmed by other studies on the topic [6].

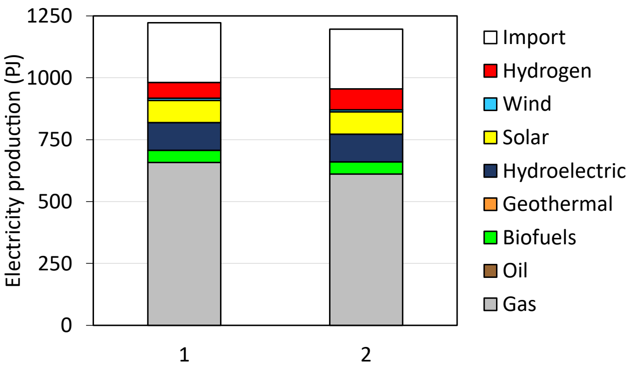

Fig. 2 Electricity mix by source in 2050. Comparison between scenarios 1 and 2.

Focusing now on the differences between the results, a variation was detected in the transport sector energy mix, presenting a higher consumption of diesel fuel (+18%) and a lower electricity consumption (-47%) (see Fig. 3a) consistently with the HRs variation (although the electricity consumption is very low even in scenario 1). This difference is mostly due to a slight technology shift in the freight road vehicles fleet, without any electric vehicles penetration in the scenario 2 (Fig. 3b). The absence of electric vehicles also implies a higher energy consumption for the subsector (+5%), involving less efficient technology equipped with internal combustion engines.

The industry optimal energy and technology mixes seem not to be significantly affected by the HRs variation. Instead, as expected, relevant differences

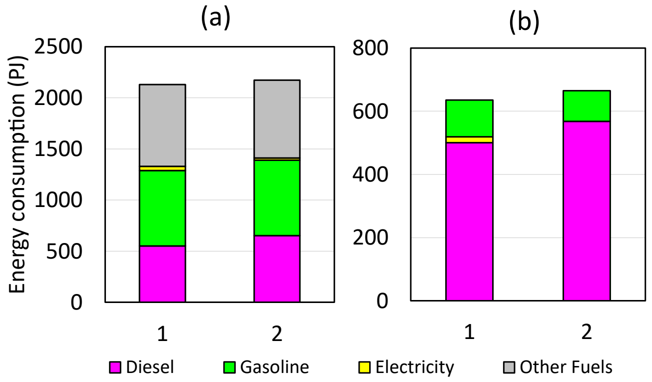

Fig. 3 Final energy consumption of the transport sector (a) and of freight road vehicles (b) in 2050. Comparison between scenarios 1 and 2.

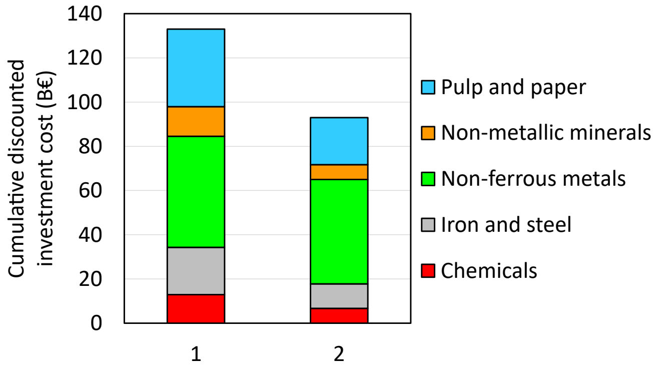

Fig. 4 Cumulative discounted investment cost breakdown by industrial subsector. Comparison between scenarios 1 and 2.

occur comparing the discounted investment costs of the selected technologies.For instance, Fig. 4 shows the cumulative discounted investment cost for the industrial sector and the breakdown by subsector. A decrease in the discounted cost (consistent with the decrease in the HRs shown in Table *3* for industry and with Eq. (3)-(4)) can be appreciated for all the industrial subsectors. The maximum percentage reduction occurs for non-metallic minerals (-50%), which is the subsector affected by the highest HR reduction. In this regard, the punctual calculation of HRs increases the accuracy of investment cost calculations, allowing for clearer and more reliable insights.

4. CONCLUSIONS AND PERSPECTIVE

A methodology to properly evaluate HRs for most of the technologies typically included in energy system optimisation models was presented. Both the well-established WACC method and the extensively studied existing literature were used to generate a wide, referenced, and open-source dataset. The appropriate choice of HRs becomes relevant in the perspective to provide relevant policy insights related to clean finance investments, especially considering that the values used in many models are usually based on "educated guesses": most of these values are taken from third sources, without explicit details on the underlying assumptions or implications of their choice, and this work aims to overcome such limitations.

The presented results of the integration of the updated HRs in the database of TEMOA-Italy highlighted no significant differences with respect to the original model version. This suggests that HRs play a minor role in determining the optimal system configuration, as other analyses confirm. The few variations presented are consistent with the HRs update. On the other hand, the discounted costs computed by the model significantly vary, according to the rate variation, providing more precise cost evaluation and allowing for more reliable policy prescriptions.

The model behavior and low sensitivity to HRs should also be investigated in other scenarios (e.g., including decarbonisation targets, carbon price, etc.) and the study could also be extended to other technologies not yet involved by the presented update. Eventually, the effects of implementing the EU Taxonomy for Sustainable Activities (boosting or penalising investments on a sustainability-based approach) should be assessed, together with the model sensitivity to the social discount rate.

DECLARATION OF INTEREST STATEMENT

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. All authors read and approved the final manuscript.

REFERENCES

[1] IEA, “World Energy Investment 2022 – Analysis - IEA.” Accessed: Sep. 14, 2023. [Online]. Available: https://www.iea.org/reports/world-energy-investment-2022

[2] M. G. Prina, G. Manzolini, D. Moser, B. Nastasi, and W. Sparber, “Classification and challenges of bottom-up energy system models - A review,” *Renewable and Sustainable Energy Reviews*, vol. 129, p. 109917, Sep. 2020, doi: 10.1016/J.RSER.2020.109917.

[3] Loulou R, Goldstein G, Kanudia A, Lettila A, and Remme U, “Documentation for the TIMES Model: Part I,” 2016. Accessed: Oct. 17, 2022. [Online]. Available: http://www.iea-etsap.org/web/Documentation.asp

[4] TemoaProject, “GitHub - TemoaProject/temoa,” GitHub. Accessed: Feb. 11, 2023. [Online]. Available: https://github.com/TemoaProject/temoa

[5] “EU taxonomy for sustainable activities | European Commission.” Accessed: Jul. 05, 2022. [Online]. Available: https://ec.europa.eu/info/business-economy-euro/banking-and-finance/sustainable-finance/eu-taxonomy-sustainable-activities_en

[6] D. García-Gusano, K. Espegren, A. Lind, and M. Kirkengen, “The role of the discount rates in energy systems optimisation models,” *Renewable and Sustainable Energy Reviews*, vol. 59, pp. 56–72, Jun. 2016, doi: 10.1016/J.RSER.2015.12.359.

[7] W. Nijs and P. Ruiz, “JRC-EU-TIMES Full Model,” European Commission, Joint Research Centre (JRC). Accessed: May 09, 2022. [Online]. Available: http://data.europa.eu/89h/8141a398-41a8-42fa-81a4-5b825a51761b

[8] “IEA-ETSAP | Energy Systems Analysis.” Accessed: Sep. 14, 2023. [Online]. Available: https://www.iea -etsap.org/

[9] T. Napp *et al.*, “Representing the behavioural dimension of energy demand in stringent mitigation scenarios,” 2015. Accessed: Sep. 14, 2023. [Online]. Available: https://www.researchgate.net/publication/322625457_Representing_the_behavioural_dimension_of_energy_demand_in_stringent_mitigation_scenarios

[10] 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.

[11] M. Nicoli, “A TIMES-like open-source model for the Italian energy system,” Politecnico di Torino, Turin, 2021. Accessed: Jul. 05, 2022. [Online]. Available: https://webthesis.biblio.polito.it/18850/

[12] D. Hillier, S. Ross, R. Westerfield, J. Jaffe, and B. Jordan, *Corporate finance*, 4th ed.

[13] J. Finke, V. Bertsch, and V. Di Cosmo, “Exploring the feasibility of Europe’s renewable expansion plans based on their profitability in the market,” *Energy Policy*, vol. 177, p. 113566, Jun. 2023, doi: 10.1016/J.ENPOL.2023.113566.

[14] D. Angelopoulos *et al.*, “Risks and cost of capital for onshore wind energy investments in EU countries,” *http://dx.doi.org/10.1177/0958305X16638573*, vol. 27, no. 1, pp. 82–104, Mar. 2016, doi: 10.1177/0958305X16638573.

[15] Eurelectric, “The financial situation of the Electricity Industry-Economic and financial update A EURELECTRIC report,” 2013.

[16] Salvidio and partners, “INDUSTRY BETAS,” 2018.

[17] A. Damodaran, “Cost of Capital by Industry,” NYU Stern School of Business. Accessed: Nov. 20, 2022. [Online]. Available: https://pages.stern.nyu.edu/~adamodar/pc/archives/waccemerg18.xls

[18] “LEGGE 28 dicembre 2015, n. 208,” Gazzetta Ufficiale. Accessed: Sep. 11, 2023. [Online]. Available: https://www.gazzettaufficiale.it/eli/id/2015/12/30/15G00222/sg

[19] Ministero dell’Economia e delle Finanze, “Principali Tassi di interesse - MEF Dipartimento del Tesoro.” Accessed: Sep. 11, 2023. [Online]. Available:https://www.dt.mef.gov.it/it/debitopubblico/dati_statistici/principali_tassi_di_interesse/

[20] NYU Stern School of Business, “Damodaram archive,” ctryprem17.xls. Accessed: Sep. 11, 2023. [Online]. Available: https://pages.stern.nyu.edu/~adamodar/pc/archives/

[21] Federal Reserve, “Interest Rates: Long-Term Government Bond Yields: 10-Year: Main (Including Benchmark) for Germany.” Accessed: Sep. 11, 2023. [Online]. Available: https://fred.stlouisfed.org/series/IRLTLT01DEM156N

[22] World Government Bonds, “Italy 10 Years vs Germany 10 Years Spread.” Accessed: Sep. 11, 2023. [Online]. Available: http://www.worldgovernmentbonds.com/spread/italy-10-years-vs-germany-10-years/

[23] F. Polzin *et al.*, “The effect of differentiating costs of capital by country and technology on the European energy transition,” *Clim Change*, vol. 167, no. 1–2, pp. 1–21, Jul. 2021, doi: 10.1007/S10584-021-03163-4/FIGURES/4.

[24] International Energy Agency (IEA), “The Future of Hydrogen,” 2019. Accessed: Jan. 31, 2023. [Online]. Available: https://www.iea.org/reports/the-future-of-hydrogen

[25] TemoaProject, “Temoa Project Documentation.” Accessed: Jul. 12, 2023. [Online]. Available: https://temoacloud.com/temoaproject/index.html

[26] 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

[27] MAHTEP Group, “MAHTEP/TEMOA-Italy,” Git Hub. Accessed: May 11, 2022. [Online]. Available: https://github.com/MAHTEP/TEMOA-Italy

[28] A. Balbo, G. Colucci, M. Nicoli, and L. Savoldi, “Exploring the Role of Hydrogen to Achieve the Italian Decarbonization Targets Using an Open-Source Energy System Optimization Model,” in *International Journal of Energy and Power*

Engineering, E. and T. World Academy of Science, Ed., Mar. 2023, pp. 89–100. Accessed: Apr. 25, 2023. [Online]. Available: https://publications.waset.org/10013040/exploring-the-role-of-hydrogen-to-achieve-the-italian-decarbonization-targets-using-an-open-source-energy-system-optimization-model

[29] 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.

[30] 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*, 2022, doi: 10.46855/energy-proceedings-10294.

[31] D. Lerede, C. Bustreo, F. Gracceva, M. Saccone, and L. Savoldi, "Techno-economic and environmental characterization of industrial technologies for transparent bottom-up energy modeling," *Renewable and Sustainable Energy Reviews*, vol. 140, p. 110742, Apr. 2021, doi: 10.1016/j.rser.2021.110742.

[32] S. Laera, "Development of a methodology to evaluate technology-specific discount rates for energy system optimization models," Politecnico di Torino, 2023. Accessed: Sep. 07, 2023. [Online]. Available:https://webthesis.biblio.polito.it/27422