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Development of a methodology to evaluate technology-specific discount rates for energy system optimization models

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Summary

Abstract

The urgency to develop strategies to support clean energy investments to tackle the current climate and socio-economic challenges is significantly increasing the interest in energy system models, which aim to assess the effectiveness of possible energy transition policies in pursuing climate targets. Among these tools, energy system optimization models (ESOMs) are widely used to find the least-cost configuration of the technological network which allows to satisfy the final energy service demands, in a certain region, and along a certain time horizon under a set of user-defined constraints (including, e.g., greenhouse gases emission trajectories). ESOMs rely on a detailed techno-economic characterization of the technologies included in the energy system and are thus defined “bottom-up models”. While the cost trajectories for both well-established and innovative technologies are defined according to the available literature, technology-specific discount rates, also referred to as hurdle rates, are often based on educated guesses. In some models, high hurdle rates are adopted to represent the barriers for investments in innovative, high-risk energy projects (e.g., investments in nuclear technologies).

This work is devoted to the establishment of a rigorous methodology to define hurdle rates for technologies typically composing the Reference Energy Systems of ESOMs. The proposed methodology was then applied to the open-source TEMOA-Italy model instance, representative of the Italian Energy System.

The results given by TEMOA-Italy were compared with those coming from the previous version of the database, in which the hurdle rates were assigned to few technologies based on assumptions and/or educated guesses. It came out that, despite a variation of the hurdle rates does not always significantly affect the technology competition, the analysis is however enriched by considering risks not accounted before.

The business-as-usual (BAU) examined scenario with updated hurdle rates was then used in the subsequent steps of this study as a benchmark to compare the impact of new policies. Indeed, the parameters elaborated to evaluate the hurdle rates were revised in the light of the guidelines of the EU Taxonomy. This work focuses on EU Taxonomy Mitigation Technology Screening Criteria (TSC), which mainly refer on emissions and electricity consumption of technologies. Although no noteworthy differences from the BAU scenario were revealed, the role of Taxonomy becomes interesting when combined with decarbonisation scenarios.

List of acronyms

BAU	Business-as-Usual
BOF	Basic Oxygen Furnace
CCS	Carbon Capture and Storage
CCUS	Carbon Capture Utilisation and Storage
ESG	Environmental, Social and Governance
ESOM	Energy System Optimization Model
EV	Electric Vehicle
GHG	Greenhouse Gases
GWP	Global Warming Potential
H2	Hydrogen
IEA	International Energy Agency
IPCC	Intergovernmental Panel on Climate Change
IRR	Internal Rate of Return
LCV	Light Commercial Vehicle
LULUCF	Land Use, Land Use Change and Forestry
MAHTEP	Modelling of Advanced Heat Transfer and Energy Problems
MARKAL	MARKet ALlocation
MARR	Minimum Acceptable Rate of Return
MSS	Minimum Social Safeguards
NPV	Net Present Value
NZE	Net-Zero Emissions
O&M	Operational and Maintenance
RES	Reference Energy System
SCOP	Seasonal Coefficient of Performance
SQL	Structured Query Language
TEMOA	Tools for Energy Model Optimization and Analysis
TIMES	The Integrated MARKAL-EFOM System
TSC	Technical Screening Criteria
UNECE	United Nations Economic Commission for Europe
WACC	Weighted Average Cost of Capital

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1. Introduction

1.1. The need for clean finance investments

Unlocking the investments in green solutions is a crucial instrument to tackle the current energy crisis, thus allowing to ensure energy security in the short term and to get the world on a net zero track in the long term. According to the International Energy Agency (IEA), while the announced policy pledges are expected to push annual global investments in clean energy up to USD 3 trillion in 2030, this value should increase up to USD 4.6 trillion in 2030 to bring global energy-related carbon dioxide emissions to net zero by 2050, and give the world an even chance of limiting the global temperature rise to 1.5 °C with respect to the pre-industrial era (see Figure 1). Indeed, the annual average growth rate in clean energy investment in the five years after the signature of the Paris Agreement in 2015 was just over 2%, but since 2020 it has risen to 12% per year [1], meaning that, finally, clean energy investments are significantly increasing, even if they still need to be boosted to meet the international climate targets. The highest clean energy investment levels in 2021 were in China (USD 380 billion), followed by the European Union (USD 260 billion) and the United States (USD 215 billion) [1]. Particularly, in advanced economies, in 2021 sustainable debt issuances surpassed USD 1.7 trillion [1], predominantly consisting of green bonds aimed at funding renewable energy, eco-friendly buildings, and sustainable transport. Additionally, there was a surge in sustainability-linked debt, which is dependent on meeting specific targets such as reducing company-wide emissions, rather than being restricted to project-based financing.

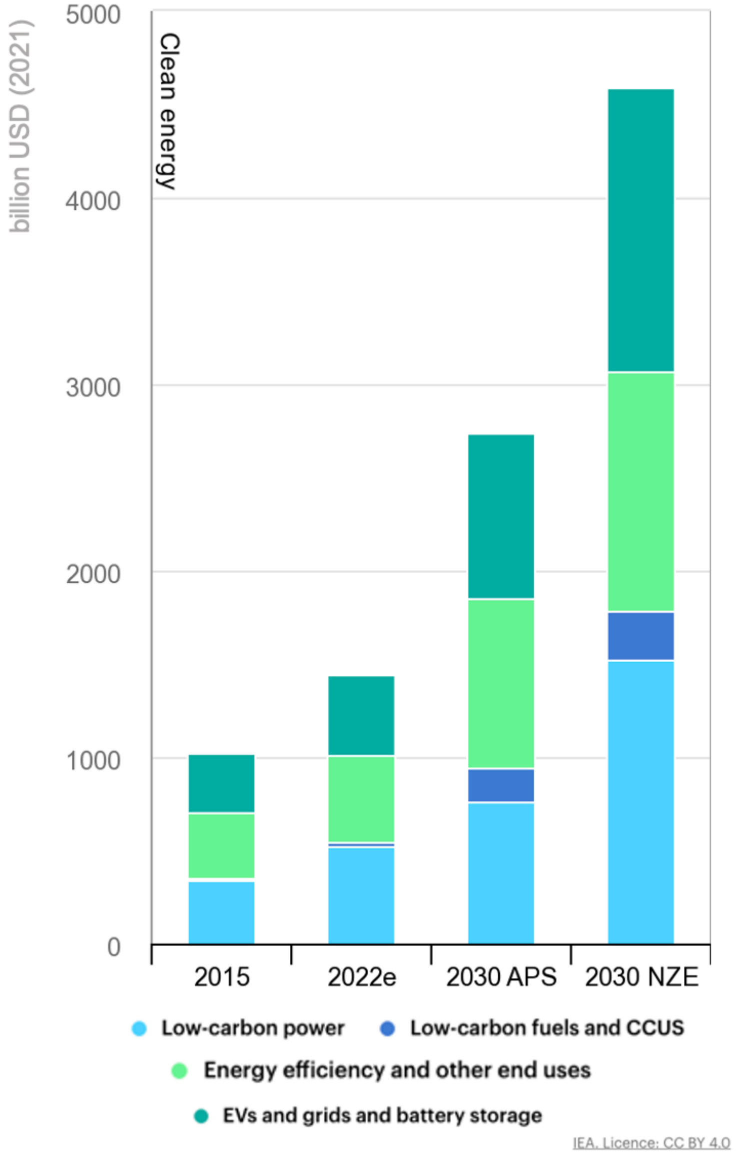


Figure 1. Annual global energy investment benchmarked against the needs in 2030 in IEA scenarios, 2015-2030 [1].

Nevertheless, higher energy prices affecting essential construction materials like steel and cement, combined with pressures on multiple supply chains are increasing the costs of fossil fuel supply as well as of clean energy technologies. Indeed, after years of declines, the costs of solar panels and wind turbines increased between 10% and 20% since 2020 [1]. Therefore, alleviating the burden on consumers shall be a priority in a country's policy agenda. Furthermore, the current energy crisis has turned into a sort of dilemma for Environmental, Social and Governance (ESG) investing. From one side, ESG strategies seem to strand assets that emit but are still considered essential to ensure energy security in the short run, while on the other hand they are considered ineffective. In this regard, the alignment of ESG taxonomies and the standardization of reporting frameworks is a priority [1]. Indeed, information gaps and short-termism typically represent challenges for investors to originate and invest in clean energy assets [2]. This should be a matter of concern as the decisions taken today by banks and investors steer the future economy and subsequently drive the evolution of the energy system.

As for the EU, in compliance with its long-term strategy that envisages the achievement of net-zero Greenhouse Gases (GHG) emissions by 2050, it started to develop a community strategy on sustainable finance in 2018 [3]. Indeed, at that time, the European Commission published an Action Plan on Financing Sustainable Growth [4], built on recommendations made by the High-Level Expert Group. The Action Plan established three objectives:

1. Redirect capital flows towards sustainable investment.
2. Mainstream sustainability in risk management.
3. Foster transparency and long-termism.

In this perspective, the EU Taxonomy forms a part of the implementation of the Action Plan on Financing Sustainable Growth as it is intended to be a classification system to determine whether an economic activity is environmentally sustainable. The EU Taxonomy Regulation was published in the Official Journal of the EU on 22nd June 2020 and entered into force on 12th July 2020. The rationale behind it is to create security for investors, protect private investors from greenwashing, help companies to become more climate-friendly, mitigate market fragmentation, and help shift investments where they are most needed [5]. The EU banking sector, which represents around 80% of the debt funding of the entire EU economy [6], has welcomed the EU Taxonomy as a clear guidance, providing support to identify green assets, set targets and align their business strategies with the clean energy transition. Once applied, several banks agree on the benefits that the EU Taxonomy can bring, and namely [6]:

- Levelling the playing field in the banking sector and reputational enhancement, i.e., “reducing greenwashing”.
- Increasing business opportunities and potentially increasing demand for sustainable finance products.
- Fostering coherence and alignment with national and international standards.

1.2. Energy systems optimization models

The EU Taxonomy is only one of several examples of policy instruments that can be and are being applied to the energy sector to push it in a more environmentally and socio-economically sustainable direction.

Nevertheless, the effectiveness of possible energy transition policies must be tested. That’s where energy system modelling comes in. The energy models were first developed during the 1970s and perceived as useful tools for understanding how to address the oil crisis [7]. As soon as awareness of the inexorable climate challenges grew, interest in such models picked up again, increasing even more following the Russian invasion of Ukraine, which struck at the heart of the European energy system. According to the Intergovernmental Panel on Climate Change (IPCC), energy system models comprehend all components related to the production, conversion, delivery, and use of energy [8]. In turn, energy modelling is used to investigate the current state of the energy system and its future evolution, aiming to find the most profitable or sustainable investments and providing with energy planning guidelines and recommendations. Among the different types of energy models, the multi-scenario analysis of this work is carried out using a bottom-up energy system optimization model (ESOM). ESOMs are used to evaluate the optimal configuration of the energy systems which allows to minimize the overall economic cost of the system. Indeed, optimization process is led by the objective function which, typically, includes investment, operation, and maintenance costs. Bottom-up models distinguish for their high level of granularity, as they require a detailed description of both technical and economic parameters of the technologies involved on both the supply (i.e., extraction of fossil fuels, use of renewable energy sources, energy transformation and trade, electricity, and heat production) and demand side (i.e., transports, buildings, commercial activities, industry). Given such high level of disaggregation, usually those input data are collected in a database [9].

ESOMs present the following features [9]:

- The optimization criterion is the minimization of the overall cost of the energy system (that equals the sum of producers' and consumers' surpluses when considering demands inelastic to their prices)
- They can work on single- or multi-regional spatial scales
- The time scale is usually long, in the order of decades, and infra-annual dynamics are modelled through time slices (i.e., more or less refined fractions of a year). Milestone years are defined as representative for longer periods (e.g., a decade) and the outcomes are computed period for the single milestone years and considered constant in the whole period
- Economic parameters evolve according to exogenous assumptions.
- The demand of energy-intensive goods and services (e.g., space heating, steel production, transport of passengers) is driven by socio-economic variables (e.g., GDP, population), often derived through econometric models
- The involvement of physical or engineering connections between energy and energy utilisation processes

Furthermore, the technology-rich description of the system, considered as one of the main advantages of ESOMs, can be appreciated looking at the parameters used to define a technology, namely [10]:

- **Efficiency**: it defines the amount of output commodity produced per unit of input commodity consumed.
- **Existing capacity**: it defines the available capacity in the existing year/years of the modelling time horizon (i.e., those periods for which the composition of the energy system is prescribed, not computed according to the optimization algorithm).
- **Lifetime**: it defines the expected useful lifespan of the technology.
- **Capacity factor**: it defines the percentage of time the technology is available for production, generally accounting for technical downtimes or the unavailability of natural resources.
- **Costs**: Investment, variable and fixed operation and maintenance costs.
- **Emission factor**: it can be associated both to commodities and to technologies [11] .

Among the parameters involved into the description of a technology, ESOMs [12] may also use technology-specific discount rates, also referred to as hurdle rates, to represent the barrier for investments in innovative, high-risk energy projects. While the cost trajectories for both well-established and innovative technologies are defined based on literature using an exogenous learning approach, technology-specific discount rates are often based on educated guesses. Moreover, there seems to be a gap in the literature in terms of analysis on the role of discount rates and a clear methodology to determine them has not been established yet. The same applies to the social discount rate, which in ESOMs is instead used to discount the stream of annual costs to a predefined reference year.

1.3. The aim of the work

The purpose of this thesis was to establish a methodology to clearly evaluate the hurdle of the technologies typically composing the Reference Energy Systems of ESOMs and, in turn, to analyse the impact of this parameter on the evolution of the energy system. In addition, the methodology was then combined with the EU Taxonomy Regulation.

First, both discount rate and the EU Taxonomy Regulation concepts were introduced in the second chapter. Afterwards, in the third chapter, an overview of the state of the art of the use and the evaluation of discount rates in energy system modelling is given, thus remarking on the existing criticalities, too.

The developed methodology was then explained in the fourth chapter, where the economic parameters and the assumptions made to evaluate the hurdle rates were outlined. The rationale behind the code written to assign the hurdle rates to the technologies typically modelled in the ESOMs was then described. In particular, in this work, the ESOM chosen was TEMOA-Italy, an open-source model instance representative of the Italian Reference Energy System. The focus was then moved towards the integration within the methodology of the EU Taxonomy mitigation criteria to clearly distinguish green from brown investments.

In the fifth chapter, several scenarios were implemented. First, in order to assess the role of the hurdle rates in affecting the evolution of the Italian Reference Energy System, the results obtained by applying the methodology were compared to the one obtained with the former version of the TEMOA-Italy database. Finally, the Taxonomy scheme was combined with different decarbonisation pathways to understand whether it allows promoting the deployment of clean energy investments needed to achieve the net-zero targets by 2050.

2. Discount rates and the EU Taxonomy Regulation

2.1. Hurdle and social discount rates

According to the European Commission, the discount rate is the degree at which future values are discounted to the present [13]. The purpose of using a discount rate is to adjust all costs and benefits to their present values, allowing them to be compared against each other. By calculating the present value of the differences between the costs and benefits over time, the net present value (NPV) of a particular option is obtained. The NPV is the primary criterion for determining whether a particular investment is justified. The discounting factor D_t to calculate the NPV is given by Eq. (1), where r is the discount rate and t is the time in years.

$$D_t = \frac{1}{(1+r)^t} \tag{1}$$

When utilizing the discounting formula presented in Eq. (1), it is important to distinguish between the financial and the social discount rate. Whilst the first characterizes private investments, the social discount rate is a concept that tries to capture the societal perspective on how future outcomes should be valued in relation to present outcomes [12]. Governments are typically responsible for selecting the social discount rate as they represent the entirety of society and are accountable for factors such as environmental issues, moral principles, sustainability, economic growth, and security. Conversely, the financial discount rate does not necessarily consider social considerations such as welfare or sustainability and it should represent the opportunity cost of what else the firm could accomplish with those same funds.

In this perspective, the hurdle rate of a project is defined as the minimum financial discount rate a company is willing to accept before starting the project itself, given its risk and the opportunity cost of forgoing other projects. Indeed, the hurdle rate is also known as the minimum acceptable rate of return (MARR), which corresponds to the minimum required rate of return or target rate that investors are expecting to receive on an investment. Before accepting and implementing a certain investment project, its internal rate of return (IRR) should be equal to or greater than the hurdle rate. Besides, the IRR is the discount rate that would give a project a NPV of zero so that the expected income perfectly balances the initial investment.

$$NPV = \sum_{n=0}^{N} \frac{C_n}{(1+r)^n} = 0 \tag{2}$$

In Eq. (2) C_n is the cash flow in the period n and the NPV function is given for N-integer (number of periods). Therefore, any potential investments must have a higher return rate than its hurdle rate to be acceptable in the long run.

For each investment, the hurdle rate accounts for specific risks and barriers, thus acting as a benchmark for comparison between the worthiness of a particular investment and associated risk. According to [14], the hurdle rate accounts for the following risks (see Table 1):

1) Systematic risks, i.e., risks correlated with the general market portfolio that cannot be diversified by holding a portfolio of assets.
2) Asymmetric risks, i.e., risks that have an asymmetric impact on expected project return, typically with a large downside risk, not offset by a commensurate upside.
3) Option Values, i.e., the premium derived from foregoing the option to wait and see how uncertainty resolves over time.

Table 1. Types of risks accounted by the hurdle rate.

Symmetric risks	**Asymmetric risks**	**Option values**
• Volatility of revenues (especially for assets that have large upfront capital outlays that must be recovered over several years or decades, and technologies with long construction lead times **[15]** • Fuel price volatility • Foreign exchange risk (i.e., risk of unfavourable fluctuations in the exchange rate of the currency in which a significant portion of the generator's input costs are denominated) • Carbon price levels and volatility (for high-emitting industrial activities whose marginal cost reflect the cost of carbon)	• Policy risk (related not only to the overall structure of future market arrangements, but also to specific aspects, such as incentives or tax treatment of investments) • Construction delay risk • Technology maturity risk (i.e., the risk of unforeseen underperformance or higher cost for emerging technologies)	• Novelty premium, due to the uncertainty about the future path of energy policy, investors may derive value from deferring investment, i.e., adopting a “wait and see” approach. The “novelty premium” is defined as the additional return that investors would price in for their loss of optionality to wait for uncertainty around the new policy to resolve.

On the contrary, the social discount rate can be seen as the rate at which consumption should increase in the future to keep social welfare constant, given a unit reduction in consumption today [16].

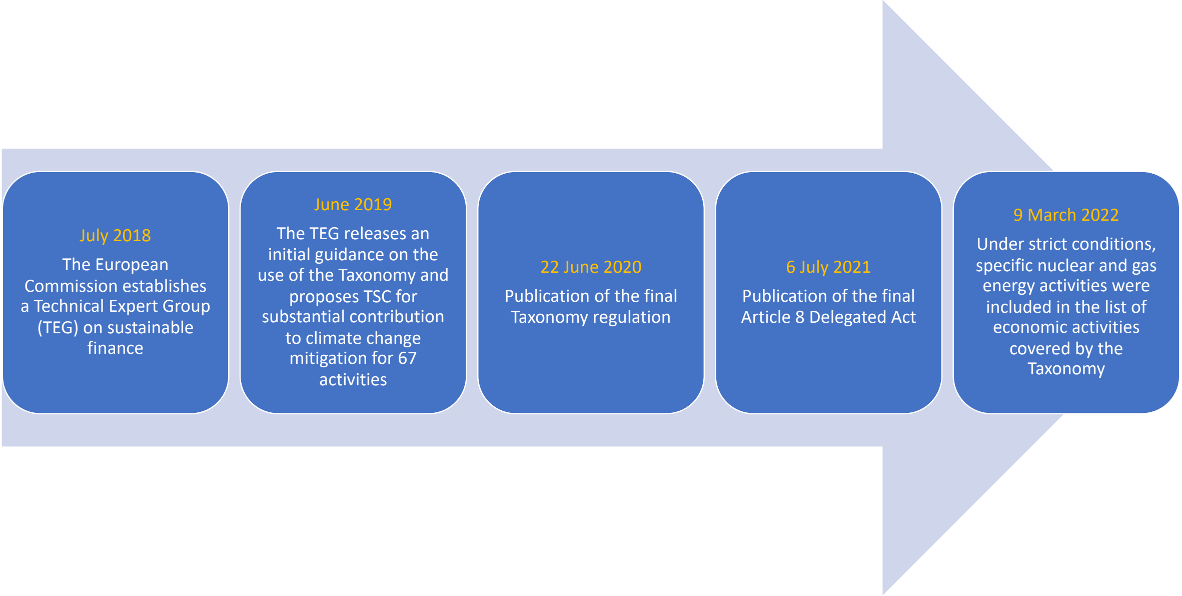
Particularly, this type of discount rate considers two factors: the social rate of time preference, which represents society's preference for present consumption over future consumption, and the diminishing marginal utility of consumption, which describes the decrease in satisfaction or usefulness that occurs as wealth increases. In fact, conventionally, the formula developed by Ramsey [17] is used, where the social discount rate r_s is expressed as it follows:

$$r_s = d + h \times g \tag{3}$$

where g is the expected average annual real economic growth rate, d stands for a "pure time preference", and h is a parameter that describes people's risk aversion and inequality aversion. The rationale for the inclusion of the growth rate g is that economic growth makes a given cost for future generations more accessible than it appears to us now. In addition, the effect of future wealth is modulated by h, whilst d reflects people's intrinsic preference for the present, or their "impatience" [18]. All the three quantities present in Eq. (3) can be quantitively estimated with some degree of uncertainty. Future growth rates can be estimated by economic modelling (e.g., Nordhaus, 2007), risk aversion can be inferred from asset markets (e.g., Epstein and Zin, 1991) and behavioural surveys (e.g., Barsky et al., 1997), and pure time preference can be inferred by behavioural experiment (e.g., Zauberman et al., 2009). On the same time, ethical considerations also come into play too when determining the value of g, as concepts like risk aversion and inequality aversion are subjective moral constructs. Hence, choosing a proper value may lead to controversies [16], as it comes to discussions on the allocation of costs and benefits between present and future generations and on how future outcomes should be values in relation to present outcomes. In fact, the higher the social discount rate, the less weight is given to future costs and, in turn, values improperly high could underestimate future costs.

2.2. An introduction to EU Taxonomy Regulation

As stated in Recital 6 of the EU Taxonomy Regulation [19], the Taxonomy was created to provide a unified and transparent classification system for sustainable activities, aiming at reorienting capital flows towards green investments. In particular, Europe is expected to need EUR 350 billion in additional investments each year until 2030 to meet its emission reduction targets in the energy system alone, while EUR 130 billion will be needed to meet environmental goals [20]. Therefore, a tool is needed to direct the industries towards the net-zero trajectory by means of a gradual process, leaving no one behind, in accordance with the European Green Deal view [21]. Indeed, according to Article 8, the Taxonomy Regulation should deliver standardized reporting on the impact of economic activities on the pre-set environmental objectives, as well as on the lending activities of financial institutions [22]. Additionally, it could contribute to setting performance targets for benchmarking the company's activities. The scheme below resumes the main legislative steps of the EU Taxonomy.



July 2018
The European Commission establishes a Technical Expert Group (TEG) on sustainable finance

June 2019
The TEG releases an initial guidance on the use of the Taxonomy and proposes TSC for substantial contribution to climate change mitigation for 67 activities

22 June 2020
Publication of the final Taxonomy regulation

6 July 2021
Publication of the final Article 8 Delegated Act

9 March 2022
Under strict conditions, specific nuclear and gas energy activities were included in the list of economic activities covered by the Taxonomy

Figure 2. Main legislative steps of EU Taxonomy [20].

In order to be considered environmentally sustainable (namely Taxonomy-aligned), the economic activity under investigation must:

- Contribute substantially to either Mitigation or Adaptation
- Do not harm the environment in other ways
- Meets minimum social standards referred to as Minimum Social Safeguards (MSS)

The concept is illustrated in the Technical Expert Group (TEG) report [23] (see Figure 3):

Substantially contribute to at least one of the six environmental objectives as defined in the Regulation

+

Do no significant harm to any of the other five environmental objectives as defined in the proposed Regulation

+

Comply with **minimum safeguards**

Figure 3. Evaluation process of economic activities in the EU Taxonomy [23]

In particular, the key components that need to be addressed are (see Table 2):

- A set of six environmental objectives
- Four performance requirements
- Three types of Technical Screening Criteria (TSC)

Table 2. Key components of the EU Taxonomy assessment, adapted from [6]

Six Environmental Objectives	**Four performance requirements**	**Three types of TSC**
• Climate change mitigation • Climate change adaptation • Sustainable use and protection of water and marine resources • Transition to a circular economy, waste prevention and recycling • Pollution prevention and control • Protection of healthy ecosystems	• Comply with the TSC • Contribute substantially to one or more of the six environmental objectives • Do not cause significant harm to any of the remaining environmental objectives • Comply with the minimum safeguards (such as adherence to international social and business standards and conventions)	Help to evaluate: • Substantial contribution to Mitigation • Substantial contribution to Adaptation • Do not significant harm

In this work, the focus will be on activities that contribute to climate change mitigation. In particular, this occurs when the technology under investigation contributes to avoiding, reducing, or removing GHG emissions or, in the absence of low-carbon alternatives, when the activity allows limiting the global temperature rise to 1.5 °C with respect to the pre-industrial era and:

- The emissions level is the best achievable in the sector under investigation
- The activity does not hinder the development of alternative low-carbon solutions
- The activity does not lead to the lock-in of carbon-intensive assets.

The scheme below summarises the process that has to be followed in order to assess whether an activity is Taxonomy-aligned.

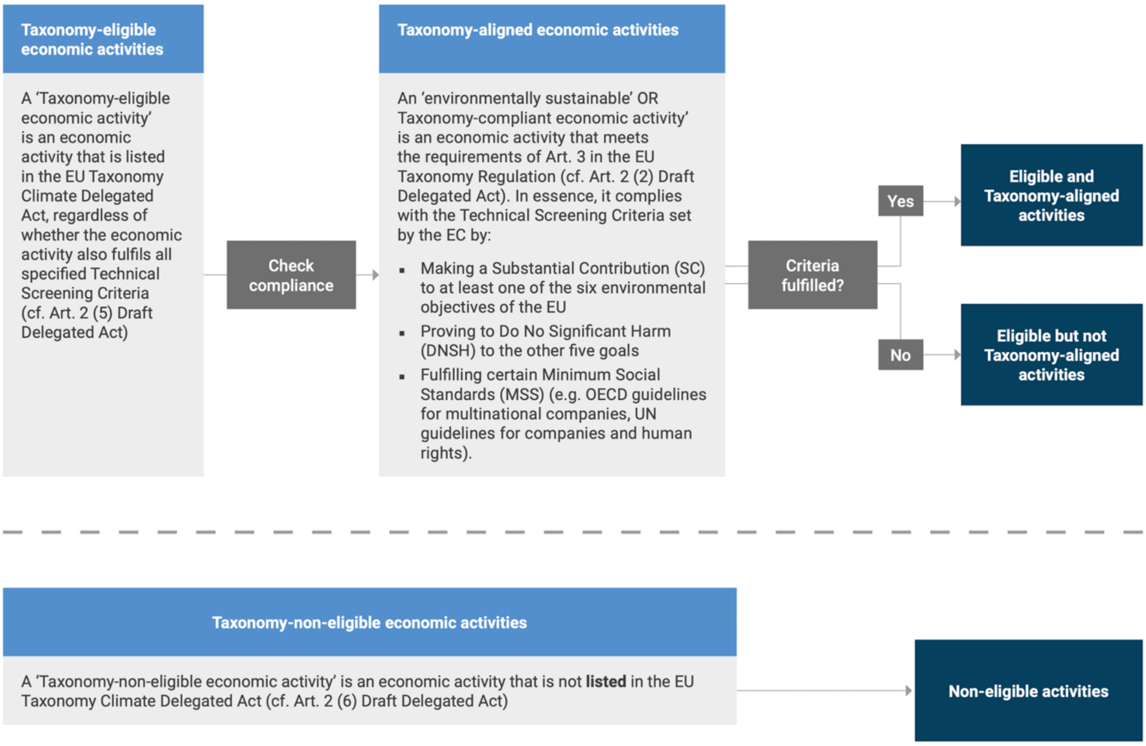


Figure 4. Scheme of the EU Taxonomy process [22]

3. The role of discount rates in energy system modelling

This chapter explores the role of discount rates in energy system modelling. First, an explanation of the meaning assumed by the hurdle rate and social discount rate within the ESOM framework is given, with a focus on TIMES. Besides, an overview of the values typically used in ESOMs is given. In turn, criticalities already identified in the existing literature are emphasized. This paves the way to the need to have a clear methodology for the evaluation of discount rates.

3.1. State of the art

Even if bottom-up models, such as TIMES (The Integrated MARKAL-EFOM System) give plenty of details for both technical and economic parameters of the technology portfolio, these types of models are often weak when certain barriers are considered [12]. Most models describe barriers in an aggregated way using an adjusted discount rate, while more advanced models have taken initial steps to further examine barriers. Nevertheless, even in the most advanced models, only a few of the observed barriers are explicitly considered. Furthermore, technology adoption is considered as a rational decision-making process, assuming perfect foresight [24].

Besides, in some models, higher hurdle rates are adopted to represent the barriers for investments such as imperfect information, limited availability of capital, hidden costs (and benefits), risk and uncertainty, split incentives, access to capital, and bounded rationality. For instance, within energy-economy models high implicit discount rates are widely used as a proxy to simulate the slow adoption of energy efficiency investments in the residential sector [25].

As for the social discount rate, according to [26], the risk assessment (as a barrier) includes several critical factors such as the investment costs, the identification of possible risks, the lack of data and the possible responses to natural danger. As a result, the key variables that need to be considered include measures to safeguard natural areas, the likelihood or frequency of natural disasters, historical data on occurrences, technical and physical details, and the identification of one of the four approaches to address identified risks - acceptance, avoidance, transfer, or mitigation.

The social discount rate explicitly appears in the objective function. In many ESOMs, for each region, the model computes the total NPV of the stream of annual costs, discounted to a reference year. Then, they are aggregated into a single total cost, namely the objective function itself. For instance, in TIMES models, the total NPV is computed as in Eq. (4).

$$NPV = \sum_{r=1}^{R} \sum_{y \in Y} \left(1 + d_{r,y}\right)^{REFYR-y} \cdot ANNCOST(r,y) \tag{4}$$

Where *ANNCOST(r,y)* is the total annual cost in region r and year y; $d_{r,y}$ is the general discount rate; *REFYR* is the reference year for discounting; *Y* is the set of years for which there are costs, including all years in the horizon, plus past years in case costs have been defined for past investments, plus a number of years after the end-of-horizon with some investment and dismantling costs to be considered, as well as the salvage value; and R is the set of regions of the model. In the case of one single region, the Eq. (2) shown previously represents the regional objective function of the model.

The following equation shows the objective function of TIMES models [27], where ANNCOST includes a list of costs affected by discounting except the salvage.

$$OBJ(z,r) = \sum_{y \in \pm\infty} DISC(y,z) \cdot \left\{ \begin{matrix} INVCOST(y) + INVTAXSUB(y) + INVDECOM(y) + \\ +FIXCOST(y) + FIXTAXSUB(y) + VARCOST(y) + \\ +ELASTCOST(y) - LATEREVENUES(y) \end{matrix} \right\} - SALVAGE(z) \tag{5}$$

Where the *DISC(y,z)* is the discount factor referred to the beginning of the year z; *INVCOST(y)* is the investment cost; *INVTAXSUB(y)* are the taxes and subsidies attached to the investments; *INVDECOM(y)* is the capital cost related to the decommissioning; *FIXCOST(y)* are the fixed annual costs; *FIXTAXSUB(y)* are the taxes and subsidies linked to the fixed costs; *VARCOST(y)* are the variable annual costs; *ELASTCOST(y)* is the cost resulting from the loss of welfare due to the reduction (or increase) of demands in a given run compared to the base run; *LATEREVENUES(y)* represent the late incomes; and *SALVAGE(z)* is the salvage value, corresponding to the estimated resale value of an asset at the end of its useful life [28].

The social discount rate that maximizes social welfare over time will return a socially optimum technology selection for which public incentive structures or sector master plans should be designed to achieve [16]. Nevertheless, involving a social discount rate does not replicate the investment behaviour observed in real-world conditions among firms or individuals. Indeed, by using a financial hurdle rate as a discount rate, a distinct question is addressed, as it provides with insights on what actions should be taken by investors to optimize their profits rather than what target should be pursued to maximize social welfare. Furthermore, it is important to remark that, in order to provide results as reliable as possible also from a social point of view, any optimization model would require the involvement of all related external costs that could lead to a social loss in welfare, such as the external costs of local air pollution and of global GHGs emissions causing environmental damages and affecting human health. However, such external costs tend to be neglected in energy system modelling, thereby negatively impacting cleaner investments [16].

Whereas the social discount rate describes situations in which markets work perfectly, and market criteria govern all the decision-making process, including also social and government dimensions, hurdle rates – higher than social – are introduced to consider market imperfections which impede investments among other barriers [12]. In particular, the hurdle rates are not properly used as discount rates as they do not discount future values into a present value. Instead, the specific hurdle rates are used in TIMES for uplifting the capital costs by increasing the total capital recovery over the project lifetime [12]. In fact, a premium is added to investments, determined according to the level of the general discount rate, the economic lifetime of a technology and the level of the hurdle rate, as shown in the following equation:

$$1 + P = \frac{CRF_s}{CRF} = \frac{1 - \frac{1}{1 + i_s}}{1 - \frac{1}{1 + i}} \cdot \frac{1 - \frac{1}{(1 + i)^{Elife}}}{1 - \frac{1}{(1 + i_s)^{Elife}}} \tag{6}$$

Where:

- CRF_s is the capital recovery factor for technology-specific discount rate.
- CRF is the capital recovery factor for the general discount rate.
- P is the technology-specific investment premium
- i_s Technology-specific discount rate
- i General discount rate
- *Elife* it the economic life of the investment

The capital recovery factor is the ratio of a constant annuity to the present value of receiving that annuity for a given length of time. Thus, Eq. (6) shows the difference in capital recovery factor between the technology-specific discount rate and the general discount rate, corresponding to the difference in net present value between applying the general discount rate and the technology-specific discount rate to a future payment stream. In turn, by applying a technology-specific discount rate within the TIMES modelling framework it is possible to add a premium on top of the lump-sum investment for a specific technology before annualising the investment through the general discount rate. Whether the technology-specific discount rate is equal to the general discount rate used in TIMES, the stream of annual payments over the economic lifetime of the technology is equivalent to the initial lump sum investment. Instead, in case the technology's discount rate differs from the general discount rate, the stream of annual payments has a different present value than the lump sum investment. Hence, the higher the hurdle rate, the higher the annual payments spread over the lifetime of an investment, thereby increasing the total cost. Therefore, hurdle rate affects only the investment costs, whilst operation and maintenance costs are unaffected. Consequently, its impact is bigger for capital-intensive technologies like nuclear and most renewable technologies. Indeed, these increased costs are then discounted back to base year by means of the global discount rate, usually set to a social discount rate value.

In TIMES modelling, usually the discount rates used are the social discount rates while, if needed, hurdle rates are included too for certain technologies. For instance, in JRC-EU-TIMES model a social discount rate of 5% was used, while different hurdle rates were considered for the different technologies of each sector, such as 8% for the centralised electricity production, 12% for the CHPs and large industries, 14% for the commercial activities, 17% for the residential sector, 11% for the freight transport and 18% for the passenger cars [29]. Concerning other studies, a sensitivity analysis on the discount rates of the nuclear technologies was conducted in [30] to analyse the impact of the nuclear policies in Switzerland. Indeed, for the nuclear technology values such as 6% and 10% were tested, while for the global discount rate of all the electricity production technologies, values from 3% to 6% and 10% were assigned. Other works that are connected to TIMES models have utilized different values for the discount rates without delving into the underlying implications or assumptions behind their selection. For example, [31], within a study to assess the bioenergy in the UK through MARKAL (MARKet and ALlocation) model, used a social discount rate of 3.5%, assuming a value compliant with the HM Treasury UK. Indeed, as for MARKAL model used for analysing the UK energy system, some authors [32] focused on the transport sector, by assigning to vehicles different values of hurdle rates, namely 5%, 10%, 20%, while other studies [33] dealt with the residential sector, considering a 25% hurdle rate for end-use technologies.

The table below shows the hurdle rate values used in some ESOMs. In most cases, as will be discussed in section 3.2, the reason why one value was preferred over another is not always clear, since these values are taken from third sources. The TIAM-Grantham is the only model, among those analysed, in which values are not simply taken from third parties but also revised considering risks and barriers such as lack of access of capital, lack of knowledge. However, the methodology is not explained.

Table 3. An overview of the values used in some ESOMs

Model	Geographical area	Sectors	Hurdle rates	Source	Application
JRC-EU-TIMES [29]	Europe	Passenger cars	18%	PRIMES model [34]	-
		Residential	17%		
		Freight transport, buses and passengers' trains	11%		
		CHP and large industry	12%		
		Other industry and commercial	14%		
		Centralised electricity generation	8%		
		Energy distribution (including grids)	7%		
ETSAP-TIAM model [35]	Western Europe	Cars, light trucks, Motorbikes, three wheelers	15%	-	-
		Heavy and medium trucks, Commercial trucks, Buses	10%		
		All Residential	15%		
		All Commercial	10%		
		All Industry	10%		
TIAM-Grantham [36]	Western Europe	Efficient conventional fuel vehicles	12%	Values given in ETSAP-TIAM model templates are revised including barriers effects (e.g., limited access to capital, lack of information, lack of infrastructure)	-
		Hybrid and electric cars, light, medium and heavy trucks, commercial trucks, buses	24%		
		All Hydrogen vehicles	32%		
		Rest of transport	5%		
		Cooking	48%		
		Water heating	48%		
		Refrigerators	52%		
		Space heating and cooling	11%		
		Other appliances	26%		
		All process related technologies	25%		
		Rest of industry	10%		
		Power sector	5%		
ETSAP-TIAM model [12]	Europe	Biomass power plants	7-10%	[15]	Scenario analysis (Low hurdle rates vs High hurdle rates)
		Natural gas steam turbine	6-9%		
		Natural gas combined cycle	6%		
		Solar photovoltaic	6-9%		
		Onshore wind power plants	7-10%		
		Offshore wind power plants	10-14%		
		Coal power technologies	5%	[29]	
		Oil power technologies	5%		
		Natural gas fuel cells	15%	ETSAP-TIAM templates [35]	
		Geothermal power plants	10%		

Looking at some results obtained in the literature, in particular with ETSAP-TIAM and the TIMES Norway models, it came out that the social discount rate impacts considerably all the energy systems as a slight variation in this value had a substantial impact on the evolution of the overall system [12]. A lower social discount rate fosters renewable energy sources and penalizes fossil fuels. This occurs because the higher the social discount rate, the lower the impact of future extra costs which tend to be higher in the case of fossil fuels-based technology. Indeed, social discounting is applied to all costs, including operational ones.

On the contrary, in most cases, changing the technology-specific hurdle rates had almost a negligible impact [12]. The effect of adding technology-specific discount rates is minor with respect to the social discount rate as it mainly affects the final amount of electricity produced with each technology, but it is not decisive in terms of the technology selection performed by the model through the optimization process. Nevertheless, hurdle rates seem to be necessary to enrich the analysis, and it should be assumed as a fine-tuning assessment [12].

3.2. Research gaps

Setting a proper value for the social discount rate can be considered as one of the crucial choices of the modelling, whilst including technology-specific discount rates is necessary to consider the risks assumed by each technology within the portfolio [12]. Therefore, caution must be paid when setting those values. For instance, since the higher the social discount rate, the less weighting is given to future costs, an inappropriately high discount rate would understate the costs of investments characterised by high upfront costs and low operational costs, such as energy efficiency measures and renewable technologies [16]. Indeed, their overall lifecycle costs would be discounted less in comparison to fossil fuel generators, which have a higher proportion of their total cost occurring over their project lifetime in the form of fuel costs. In addition, an inappropriately high hurdle rate would further disadvantage renewable energy solutions over fossil fuel as they have a higher proportion of their total costs as capital costs and, therefore, would be disproportionately affected [12].

Nevertheless, both social and technology-specific discount rates are often based on educated guesses, and the absence of discussions on discount rates is a notable concern within the community of energy optimization modellers, as evidenced by peer-reviewed papers and technical reports from various projects [12]. In fact, it is not always clear why certain values were set for the discount rates and some studies have tried to investigate the rationale behind those choices, as key figures seemed too low or high.

It is essential to point out that, while there is a vast literature on the economic parameters that influence the hurdle rate and how they vary by technology and/or type of risk, the same cannot be said about the social discount rate. So far, in fact, for the Italian Reference Energy System, the numerical values of the parameter mentioned in Eq. (3) have not been found in the literature, nor how they may evolve in the light of policy patterns on a time scale compatible with that used in the ESOMs, namely around 50 years.

Therefore, this thesis lies in the above-mentioned research gaps, providing a rigorous methodology for the selection of technology specific discount rates to be used in ESOMs. Moreover, since the methodology is developed in an open-source framework, this work is fully accessible for anyone who is willing to enrich the analysis, by considering different technologies and/or methods other than the ones currently involved.

4. Methodology

This chapter shows the method used to define the hurdle rate for supply- and demand-side technologies, and how the EU Taxonomy regulatory mitigation Technical Screening Criteria (TSC) were used to divide the technology portfolio into two categories, that are green and brown investments. First, the model used in this thesis, namely the TEMOA-Italy model [9] [37], is briefly defined, in terms of structure and main parameters to pave the way for the explanation of how the evaluation and allocation of the hurdle rate have been incorporated into the modelling framework. As for hurdle rates, the reasons for choosing one evaluation method over the others are provided, as well as the economic parameters and the equations involved, and the simplifications made due to the inaccessibility or lack of data in certain sectors. Afterwards, the procedure for assigning hurdle rates for technologies in the TEMOA-Italy database is explained. Finally, the focus is shifted towards the involvement of the EU Taxonomy mitigation criteria within the model, as instruments to clearly distinguish clean investments. In addition, a possible consequence that this classification may have on the value of hurdle rates is proposed, and particular attention is paid to its integration into the model.

4.1. The TEMOA-Italy model

The methodology developed in this work was applied to TEMOA-Italy, a model instance for the Italian energy system optimization, developed by the MAHTEP research group at PoliTO [9] within the TEMOA open modelling framework [38].

The base year of the model is 2006, and the time horizon runs until 2050. This means that the optimization is performed in between 2007 and 2050, with the historical period referred to as past future years. In this regard, the model is calibrated against the historical period until 2020.

The Reference Energy System (RES) includes the following sectors: upstream, power generation, agriculture, commercial, residential, transport and industry [9]. The figure below provides a simplified version of the RES, where the above-mentioned sectors are represented, together with their interconnections.

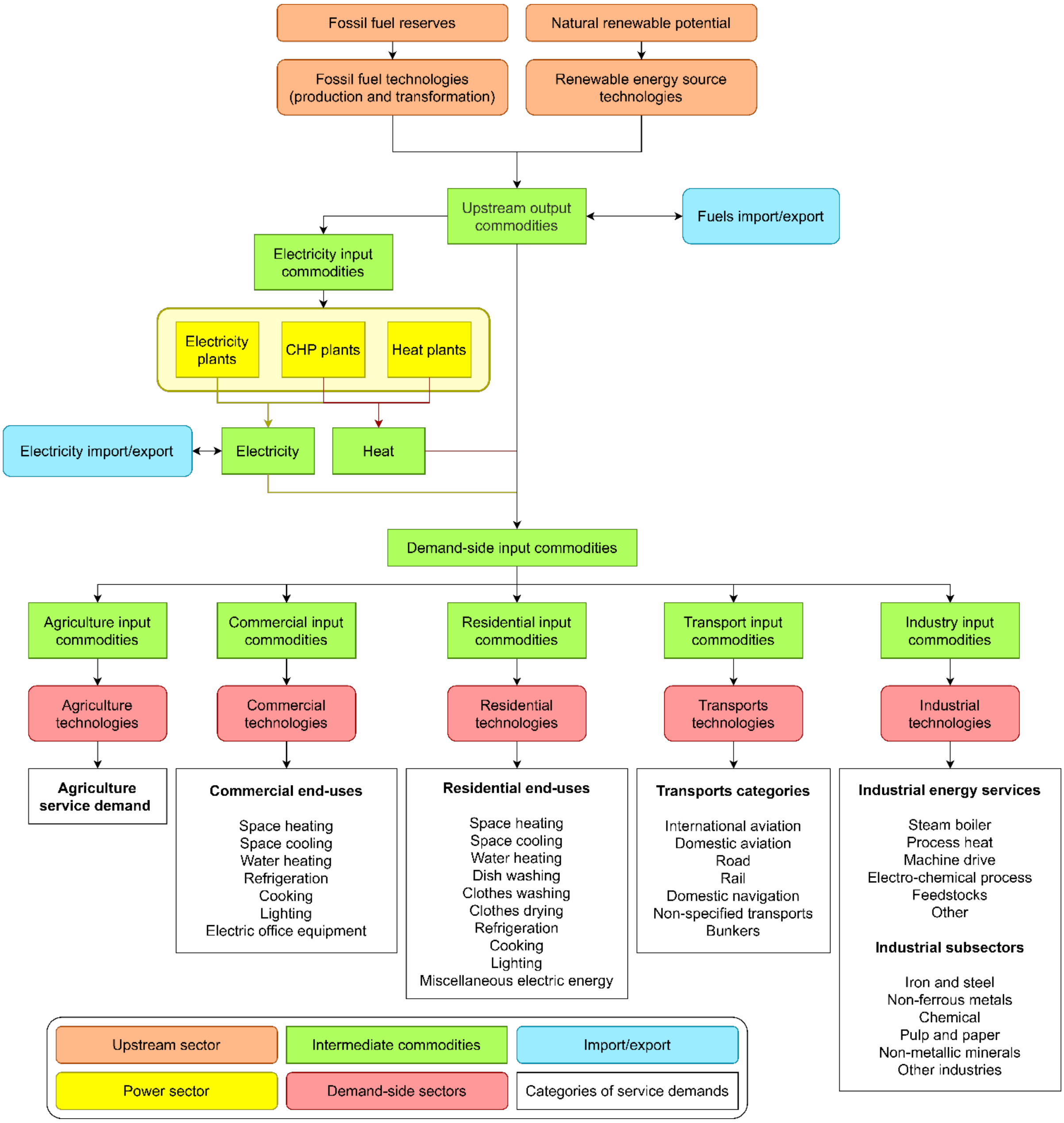


Figure 5. A simple scheme of the TEMOA-Italy reference energy system [9]

4.2. Integration of the discount rate in the TEMOA modelling framework

4.2.1. Evaluation of the technology-specific discount rate

The following methods are among the most used to evaluate hurdle rates for investments. The specific approach used depends on the nature of the investment and the preferences of the investor:

- Cost of Capital approach: the hurdle rate of the investment is evaluated considering the weighted average cost of capital (WACC), which represents the minimum return that a company needs to generate to satisfy its investors.

- Market-Based approach: the hurdle rate of the investment is estimated in compliance with the rates of return required by the market for investments with similar risk features. This method can be useful where market data is available and reliable.
- Surveys: the hurdle rate is estimated through surveys of investors or industry experts to determine the minimum acceptable rate of return for a certain investment. This approach is usually used whether market data is limited or unreliable, but it may be subjected to biases or errors in sampling the population to be interviewed.

Such methods can be used in a combined way too. For instance, in [15] the discount rate ranges for low-carbon technologies in the UK. are evaluated gathering data on hurdle rates from various academic studies and from discussions with market participants contacted as part of the survey.

In this work, the choice fell on the WACC approach, widely used in finance as it is considered as an effective indicator for assessing investment risks and quantifying the respective cost of capital [39] as well as in energy system modelling [16]. Even if usually the WACC represents the cost of raising capital, when it comes to represent the hurdle rate, it assumes the meaning of opportunity cost, that is a rate of return that a company or an investor can earn on other investments in the market of equivalent risk [16].

Furthermore, according to [40], when modelling investment decisions, the hurdle rate should be set equal to the WACC of a reference investor plus a project-specific hurdle premium. The latter accounts for project and policy risks such as what occurs if a technology becomes obsolete, a plant needs more time to be built, fixed operation and maintenance (O&M) costs reveal to be higher, high price spikes are subjected to price caps in energy sector, or new policy measures are introduced like a carbon tax. However, since all the evolutions of techno-economic parameters throughout the time horizon are known in advance (according to the perfect foresight approach usually used in ESOMs) and, moreover, the main aim of the ESOMs is not to simulate the impact of policies or shocks in the economy (as it happens for instance in Computable General Equilibrium Models) in this study, it was decided to neglect the hurdle premium. Indeed, the hurdle rate can be defined as the post-tax WACC calculated with the equation below:

$$WACC = R_e \cdot \frac{E}{E+D} + R_d \cdot \frac{D}{E+D} \cdot (1 - CTR) \tag{7}$$

Where:

- Re is the minimum equity return expectation, namely cost of equity,
- E is the market value of equity, i.e., the total dollar value of a company's equity and is also known as market capitalization,
- E/E+D is the proportion of total financing represented by equity,
- D is the total amount of interest paid by a firm or an entity to borrow capital, namely cost of debt,
- D/E+D is the proportion of total financing represented by debt,
- CTR is the corporate tax rate.

All these parameters are inputs specific to a project or corporate entity. When it comes to define a financial hurdle rate at the system level, the value assigned to the WACC should approximate a market average based on the prevailing financing trends and practices in a country [41]. Indeed, the aim is to simplify a complex environment with different investor risk preferences, sources of finance, risk mitigation options, policy constraints, etc.

Focusing on cost of debt and cost of equity, different formulas are proposed in literature for their evaluation. Indeed, the following equations have been chosen for this work [39]:

$$R_e = RfR + MRP \cdot \beta_L \tag{8}$$

Where:

- R_e is the cost of equity.
- RfR is the risk-free rate, i.e., the rate earned on riskless investments is considered a risk-free rate. It is linked directly to government bond interest rates, as they offer the most appropriate observable proxy for a riskless asset. This parameter can assume different meanings: the risk-free rate can include the country risk and then, be represented by the interest rate of the national long- term government bonds (unconditional approach) or, alternatively, the country risk is included in the market risk premium and the risk-free rate constitutes the ''real'' risk-free rate, e.g., German government bond yield (conditional approach) [42]
- MRP is the market risk premium, i.e., the return of the market portfolio in excess of the risk-free rate. Typically, survey-based approaches and estimation-based methods on historical data are used for its evaluation.
- b is a measure of risk arising from the exposure of an investment to the general market movements. As it will be discussed later, typically, beta values distinguish by economic sector and sub-sector. WACC evaluation involves levered and unlevered beta at different stages of its calculation.

In particular, the unlevered beta (b_U), known as asset beta, represents the volatility of returns without financial leverage. To calculate the unlevered beta, an investor must gather a list of comparable company betas, take the average and re-lever it based on the company's capital structure under investigation [43]. Then WACC re-levers beta to the real or ideal capital structure. Then, the levered beta (b_L) is evaluated, and it can be said that this procedure takes apart all the capital obligations for a firm and then reassembles them to understand each part's relative impact. Indeed, the levered beta is evaluated according to the following formula where b_U is the unlevered beta, CTR the corporate tax rate and D and E, respectively, the market value of debt and equity:

$$\beta_L = \beta_U \cdot \left[1 + (1 - CTR) \cdot \left(\frac{D}{E}\right)\right] \tag{9}$$

While for the cost of debt the equation proposed by Eurelectric [44] and shown in Eq. (10) was considered:

$$R_d = European\ RfR + CDS + PS \tag{10}$$

Where:

- Rd is the cost of debt.
- $European\ RfR$ is the risk-free rate at EU-level. In this case, the 40-day average of the 10-year German government bond yield is used.
- CDS is the 10-year credit default spread of the examined country. The average annual 10-year value for Italy.
- PS is the renewable energy project spread. This parameter is related to renewable project risks and represents the risk premium charged on loans by bank borrowers [45]. Nevertheless, this parameter is only mentioned in very few sources [39] [45] for renewable projects, and as no other sources were found that mentioned it or provided values, it was decided here to neglect it. Moreover, as will be mentioned later, the methodology illustrated so far for calculating the hurdle rate has not been adopted for investments in the energy sector.

Table 4 shows the values that were chosen for this thesis. Whilst *RfR*, *European RfR* and *CDS* are reported on a 10-years basis, the others are values date back to 2018. Values dating back to this year were chosen as it is the most recent year for which, as will be seen later for sectoral betas, the largest number of data was available. These values are kept constant over the entire time horizon, as it is usually done in other models [12], so it was chosen, among other things, to discard the few available data from the two-year period April 2020 to April 2022, characterised by rare market externalities (i.e., Covid-19 pandemic, post-Covid-19 recovery, Russian invasion of Ukraine).

Table 4. Values for macro-economic parameters in WACC evaluation.

CTR	RfR	MRP	EuropeanRfR	CDS
24% [46]	2.54% [47]	9.02% [48]	0.39% [49]	1.27% [50]

Concerning the other parameters, the values taken from the literature for beta [51], D/E+D and E/E+D [52] vary according to the economic sub-sector, hence according to the type of good produced. For example, the production of aluminium has a beta of 0.82 while for copper it is 1.12. Similarly, in the case of transport, D/E+D is about 50% in shipping and 63% for rail freight and passenger transport.

However, the two sources considered have slightly different levels of disaggregation. While the first tends to disaggregate the sub-sectors, distinguishing for example, for non-ferrous materials, the production of aluminium, copper, zinc, and others, in the second [52] all fall under the category 'Metals'. However, this does not apply to the transport sector, where in both cases parameters are given for 'Aviation', 'Navigation', 'Cars', 'Trucks' and 'Rail passenger and freight'. In addition, it is important to note that, in both sources, the reference area is not Italy, but Western Europe.

Particularly, in [51] industry betas are calculated as arithmetic averages of individual betas of listed companies having a minimum market capitalization of EUR 50 million in the last five years. Indeed, for each company a regression of return of company shares to market return is performed, applied over two distinctive periods of five and of two years, considering, respectively, monthly, and weekly returns. For this thesis, it was chosen to use beta values with a regression period of five years, as generally they tend to have a lower standard error [39].

Table 5. Evaluation of hurdle rates by using WACC formula for industrial and transport sector.

Industry	**Sub-industry**	**CTR**	**RfR (10Y)**	**Beta_l**	**MRP**	**CoE**	**EuropeanRfR**	**CDS**	**CoD**	**E/E+D**	**D/E+D**	**HR**
Chemicals	Commodity chemicals	24%	2.54%	0.83	9.02%	10.0%	0.39%	1.27%	1.7%	75.77%	24.23%	7.9%
	Diversified chemicals	24%	2.54%	1.13	9.02%	12.7%	0.39%	1.27%	1.7%	69.02%	30.98%	9.2%
	Fertilizers & Agricultural chemicals	24%	2.54%	1.05	9.02%	12.0%	0.39%	1.27%	1.7%	81.50%	18.50%	10.0%
	Industrial gases	24%	2.54%	0.83	9.02%	10.0%	0.39%	1.27%	1.7%	81.50%	18.50%	8.4%
Non-metallic minerals	Construction materials	24%	2.54%	1.09	9.02%	12.4%	0.39%	1.27%	1.7%	73.93%	26.07%	9.5%
	Metals & glass containers	24%	2.54%	0.65	9.02%	8.4%	0.39%	1.27%	1.7%	73.93%	26.07%	6.5%
Pulp and paper	Paper packaging + Paper products	24%	2.54%	1.13	9.02%	12.7%	0.39%	1.27%	1.7%	75.17%	24.83%	9.9%
Non-ferrous metals	Aluminium	24%	2.54%	0.82	9.02%	9.9%	0.39%	1.27%	1.7%	71.20%	28.80%	7.4%
	Diversified metals & mining	24%	2.54%	1.18	9.02%	13.2%	0.39%	1.27%	1.7%	71.20%	28.80%	9.8%
	Copper	24%	2.54%	1.12	9.02%	12.6%	0.39%	1.27%	1.7%	71.20%	28.80%	9.4%
Iron and steel	Steel	24%	2.54%	1.34	9.02%	14.6%	0.39%	1.27%	1.7%	61.54%	38.46%	9.5%
Aviation	Airlines	24%	2.54%	0.78	9.02%	9.6%	0.39%	1.27%	1.7%	56.50%	43.50%	6.0%
Navigation	Marine	24%	2.54%	0.85	9.02%	10.2%	0.39%	1.27%	1.7%	50.51%	49.49%	5.8%
Trucks Public transport Commercial vehicles	Trucking	24%	2.54%	0.91	9.02%	10.7%	0.39%	1.27%	1.7%	50.51%	49.49%	6.0%
Cars	Automobile manufacturers	24%	2.54%	1.61	9.02%	17.1%	0.39%	1.27%	1.7%	38.03%	61.97%	7.3%
Two wheels	Motorcycle manufacturers	24%	2.54%	0.92	9.02%	10.8%	0.39%	1.27%	1.7%	38.03%	61.97%	4.9%
Rail passenger and freight	Railroads	24%	2.54%	0.75	9.02%	9.3%	0.39%	1.27%	1.7%	36.69%	63.31%	4.2%

As for the power sector, due to the lack of public available data for beta, D/E+D and E/E+D, values of hurdle rates provided by research conducted on technology specific WACCs in Italy in 2015 were used [53]. Instead, since both beta and D/E values are taken from listed companies, such values are not yet available for hydrogen production, utilisation, and storage technologies. Therefore, those values were taken from other models. This approach was applied also for electric vehicles and hydrogen-based vehicles.

At this stage, the residential and commercial sector were not treated as a proper methodology should be developed to mimic consumers behaviour, thus accounting for bounded rationality.

Upstream sector was not included as well, as most of upstream technologies in TEMOA-Italy are used to represent import, regrouping of commodities, and potential of natural resources. So far, economic values about extraction and primary or secondary transformation of fossil fuel were not found in literature, while hurdle rates for carbon capture utilisation and storage (CCUS) technologies were already provided in TEMOA-Italy database. In compliant with such values, for synfuels production technology a value of 10% was chosen. A similar assumption was made for industrial processes combined with capture and storage of CO2, as it will be discussed in the following section. The table below gives an overview of the technologies involved in the hurdle rate integration within TEMOA-Italy. In particular, unless a different value is specified, TEMOA assignes the technologies a hurdle rate equal to the social discount rate (i.e., 5%) so that no premium is added to the investment according to the Eq. (6).

Table 6. Hurdle rates in TEMOA-Italy sectors

Sector	**Technology**	**Hurdle rate source**	**Value before the methdology**	**Value after the methdology**
Commercial	-	-	-	-
Industry	Commodity chemicals	WACC formula	5%	7.9%
	Diversified chemicals	WACC formula	5%	9.2%
	Fertilizers & Agricultural chemicals	WACC formula	5%	10%
	Industrial gases	WACC formula	5%	8.4%
	Construction materials	WACC formula	5%	9.5%
	Metals & glass containers	WACC formula	5%	6.5%
	Paper packaging and Paper products	WACC formula	5%	9.9%
	Aluminium production	WACC formula	5%	7.4%
	Copper production	WACC formula	5%	9.4%
	Steel production	WACC formula	5%	9.5%
	Industrial processes with CCUS	Literature	5%	15%
	Decentralised cogeneration plants	Literature	5%	10%
	Synfuels production	Literature	5%	10%
Power production	Biomass plant	Literature	10%	6.7%
	Solar PV	Literature	5%	5.7%
	Wind onshore	Literature	5%	7.6%
	Wind onshore	Literature	5%	8.6%
	Geothermal	Literature	5%	10%
	Hydropower	Literature	5%	5.2%
	Centralised cogeneration plants	TEMOA-Italy previous database	10%	10%
	Oil power plant	TEMOA-Italy previous database	10%	10%
	Coal power plant with CCUS	TEMOA-Italy previous database	10%	10%
	Natural gas power plant with CCUS	TEMOA-Italy previous database	10%	10%
	Municipal waste plant	TEMOA-Italy previous database	10%	10%
Hydrogen	Electrolysers	Literature	5%	8%
	Storage	Literature	5%	8%

	Steam methane reforming	Literature	5%	8%
	Steam methane reforming with CCUS	TEMOA-Italy previous database	10%	10%
	Fuel cells	Literature	10%	8%
Residential	-	-	-	-
Transport	Aviation	WACC formula	5%	6.0%
	Navigation	WACC formula	5%	5.8%
	Trucks	WACC formula	5%	6.0%
	Cars	WACC formula	5%	7.3%
	Two wheels	WACC formula	5%	4.9%
	Rail passenger and freight	WACC formula	5%	4.2%
	Hybrid and electric vehicles (Cars, LCV, Medium and heavy trucks, buses)	Literature	5%	24%
	All H2 vehicles	Literature	5%	32%
	H2 navigation and aviation	Literature	5%	32%
	Ammonia navigation	Literature	5%	32%
	H2 rail freight and passenger	Literature	5%	32%
Upstream	-	-	-	-

4.2.2. Application of the hurdle rates in the TEMOA-Italy model

The Python code developed in this work, namely *hurdle_p1.py* [54], calculates the hurdle rate using the WACC formula shown in Eq. (7) or assigns it according to the values taken from literature per each sub-sector or a specific type of technology. Also, this code is open source. The equations from which the hurdle rates are derived are clear and explicit, and the values of the parameters comprising them can be easily modified and updated by other users. As mentioned in section 4.2.1, other models use the WACC to estimate the technology-specific discount rate, too, but often – as in JRC-EU-TIMES, PRIMES or ETSAP-TIAM models – this is a value already packaged and calculated by third parties, so going back to the values assigned to the different economic variables at play is not always possible.

Economic parameters taken from the literature (i.e., beta, D/D+E, E/D+E) were first uniquely associated with the goods or services they produce, rather than with the technologies themselves, within a separate table contained in a .csv file [54]. For example, in this table, the beta value provided for the car transportation sector was not manually and directly associated with all the types of cars modelled in the technology database, but rather with the commodity produced as output (in this case a service rather than a good). Afterwards, such value will be assigned only to the technologies having that output commodity. This strategy makes the code independent of the technology portfolio in the database and, therefore, flexible. In fact, while technologies can be added and removed from the database, commodities are unlikely to be changed. Regarding hurdle rate values taken from the literature (see **Errore. L'origine riferimento non è stata trovata.**), a separate discussion is needed. In fact, in most cases, these are not unique by the type of output produced, but a check on the input commodity is necessary before assigning values to the technologies in the portfolio. As for the power generation sector, for instance, although the commodity produced is always the same, different values are assigned depending on the fuel used, namely coal, natural gas, wind, or solar energy. In any case, since the hurdle rate uplifts only the capital cost, it was assigned for technologies whose capital cost can be an object of optimization, namely for the ones not yet installed at the base year.

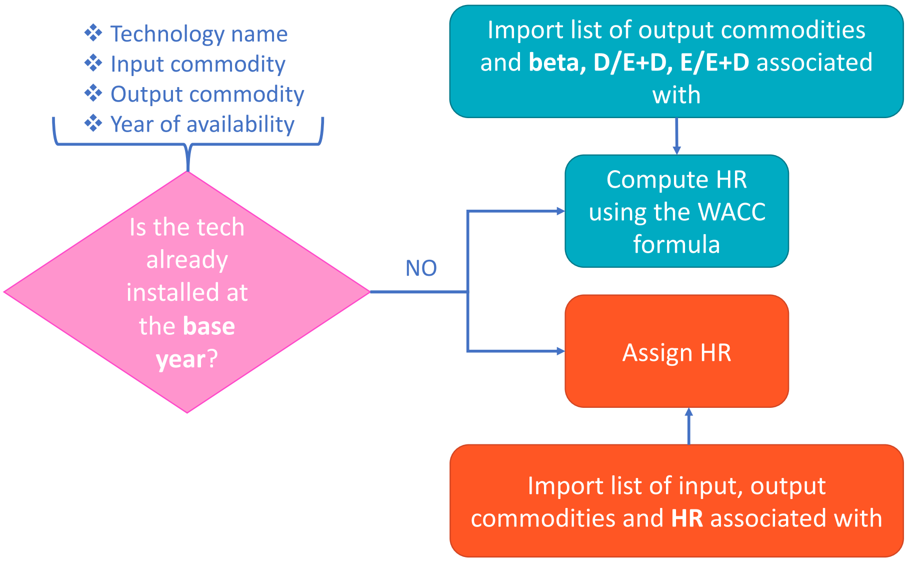


Figure 6. A simplified scheme of the hurdle_rate.py code

Concerning the application to TEMOA-Italy, it is worth mentioning that, per each technology per each milestone year of the time horizon, all the technical and economic parameters are collected in an SQLite database, in the form of tables. These data once interpolated or extrapolated for each milestone year, are ready as input for the optimization solver [9]. Before this work, the *DiscountRate* table was already present in the TEMOA-Italy database, as some hurdle rate values were given for most of the technologies in the power generation sector.

Going into detail, the code is connected to the database and communicates by means of some SQL commands. For instance, the command *SELECT* allows to pick certain information from the tables according to conditions that can be specified by the user. Indeed, the *Efficiency* table from the TEMOA-Italy database is involved, as, per each technology, it contains the name of the input and output commodity/commodities, which are needed in order to check whether for that output the literature at our disposal provides values for the economic parameters used to calculate the discount rate. Also, the years in which the technology is available to be installed are taken from *Efficiency* table, as the hurdle rate will be defined for each year.

Since the hurdle rate uplifts only the capital cost, it is fundamental to ensure that it is evaluated only for technologies whose capital cost can be object of the optimization. Therefore, information like the technology name and the year of availability – namely "vintage" – were imported from the *CostInvest* table (see Figure 7) which contains the investment costs of the stock of technologies from which the solver can draw to identify the most expensive technology mix to meet the end-use service demand of energy.

In both cases, all the parameters or values needed were then collected in proper data structures, like maps or vectors. In order to make sure that the hurdle rate allocation concerns only new technologies and not those already installed, a filter was applied to eliminate all the technologies that are in the *Efficiency* table but not in the *CostInvest* table (see Figure 7).

Indeed, for the filtered technologies, their output and input commodity were then compared with the list of input and output commodities for which hurdle rates value in literature were found (see **Errore. L'origine riferimento non è stata trovata.**). Whether both input and output commodities were included in the list, the values of hurdle rate were assigned according to the literature. Alternatively, in case the output commodity was one of those with which economic parameters (i.e., beta, D/E+D, E/E+D) were associated, the discount rate was evaluated by applying the WACC formula.

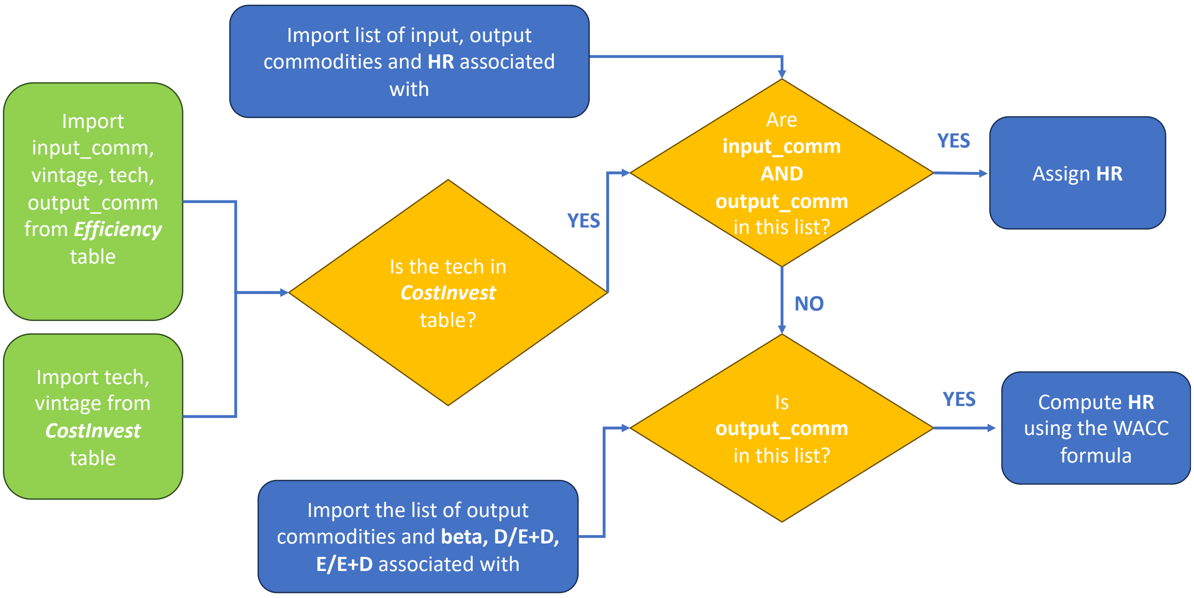


Figure 7. Flow chart of hurdle_rate.py code

However, a few cases went beyond the type of input resource used and the good/service produced, thus requiring additional controls, such as in the case of industrial processes that also involve CO2 capture. For example, in the case of iron and steel production in blast furnace-basic oxygen furnace with CO2 capture, a higher hurdle rate than the technology without CO2 capture is assigned, thus increasing from 10 per cent to 15 per cent. Notably, the latter value is the result of an assumption since a value of 10% was already set in TEMOA-Italy for all CCS or CCUS technologies. Such control was performed after the calculation of the hurdle rate, checking whether the technology was included in *LinkedTechs* table, typically used for CCS technologies [55].

4.3. Integration of the EU Taxonomy in the TEMOA modelling framework

A further step of this methodology envisages the integration of the EU Taxonomy. As already stated in section 2.2, in this project the focus is on the climate change mitigation TSC, taken from [3]. The idea was to assess whether the technologies within the TEMOA-Italy database fulfil such requirements and, in turn, to assign a premium or a penalty according to the result achieved. Before analysing the TSC and how the TEMOA-Italy technology stock has been reviewed, it is necessary describe the rationale behind the premia/penalties choice for this work.

4.3.1. The EU Taxonomy Mitigation Technology Screening Criteria: analysis and assumptions

First, it is fundamental to remark that, from now on, the expressions "Taxonomy eligible" and "Taxonomy aligned" can be considered interchangeable, as the model only allows us to verify that the activity contributes to climate change mitigation by respecting the set quantitative limits but does not allow to verify that no environmental damage is caused, or that minimum social standard are respected. This assumption must also be combined with the fact that, for the time being, the Taxonomy does not present quantitative criteria to verify the latter two conditions.

The EU Taxonomy TSC cover several activities, and thresholds can be referred to different characteristics of the technologies. In most of the cases, such characteristics were modelled in TEMOA-Italy database as well, so they could be checked. In other cases, simplifications had to be made.

For instance, the installation and operation of electric heat pumps in buildings can be considered eligible only if the refrigerant used has a Global Warming Potential (GWP) lower than 10 and the Seasonal Coefficient of Performance (SCOP) is above 3.3. As in TEMOA-Italy database no information are provided in terms of the type of refrigerant used in heat pumps, such criterion was neglected while, for SCOP, it was assumed equal to the COP, which is, instead, an available data.

As for manufacture of aluminium, hydrogen, inorganic basic chemicals and fertilisers, thresholds on indirect emissions of electricity used (i.e., average GHG emissions associated to the electricity production per unit equal to 100 gCO2e/kWh), were not taken into account as the average carbon intensity of the electricity needed to produce such products depends on the electricity mix, which is a result of the optimization process. This implies that the hurdle rate value itself would depend on a decision variable, thus introducing a non-linearity within the objective function. At this stage, it was decided to neglect all the criteria involving Scope 2 emissions (i.e., from the generation of the electricity used by a certain technology) also because, in most of the cases, the thresholds are referred to emissions directly released by the technology under investigation.

As for the permanent sequestration of captured CO2 it was assumed that the facility complies with ISO 27914:2017 for geological storage of CO2 in order to be considered eligible. Whilst, for the emissions capture technologies it was assumed that the captured CO2 will be offloaded to a Taxonomy eligible CO2 transportation operation and permanent sequestration facility.

For what concerns the power sector, a separate discussion is needed.

Table 7. EU Taxonomy climate change mitigation thresholds on power sector technologies [3].

Activity	**Threshold**	**Further comments**
Production of Electricity from: Solar PV Wind Power Hydropower Geothermal Energy Gas Combustion	The facilities must operate at life cycle emissions lower than 100 gCO2e/kWh, declining to 0 gCO2e/kWh by 2050.	This threshold must be reduced every 5 years in line with a net-zero CO2e in 2050 trajectory. Assets and activities must meet the threshold at the point in time when taxonomy approval is sought. For activities which go beyond 2050, it must be technically feasible to reach net-zero emissions.
Production of Electricity from Bioenergy	Facilities operating at less than 85% of GHG emissions in relation to the relative fossil fuel comparator set out in RED II increasing to 100% by 2050, are eligible.	This threshold must be reduced every 5 years in line with a net-zero CO2e in 2050 trajectory. Assets and activities must meet the threshold at the point in time when taxonomy approval is sought. For activities which go beyond 2050, it must be technically feasible to reach net-zero emissions.
Production of Heat/cool from: Geothermal Gas Combustion Bioenergy	Facilities operating at less than 30g CO2e/kWh (Thermal), declining to 0 g CO2e/kWh (Thermal) by 2050, are eligible.	This threshold must be reduced every 5 years in line with a net-zero CO2e in 2050 trajectory. Assets and activities must meet the threshold at the point in time when taxonomy approval is sought. For activities which go beyond 2050, it must be technically feasible to reach net-zero emissions.
Production of Heat/cool using Waste Heat	All recovery of waste heat is eligible	
Cogeneration of Heat/cool and Power from: Geothermal Energy Gas Combustion Bioenergy	The Weighted Cogeneration Threshold is calculated from the relative production of heat and power and based on the declining power generation threshold of $100\ \mathrm{gCO2e/kWh(e)}$, and a notional heat threshold of $30\ \mathrm{gCO2e/kWh(th)}$. Weighted CHP Threshold: $\frac{(30 \cdot P(th) + 100 \cdot P(e))}{P(th) + P(e)}\ \mathrm{gCO2e/kWh(th + e)}$	This threshold must be reduced every 5 years in line with a net-zero CO2e in 2050 trajectory. Assets and activities must meet the threshold at the point in time when taxonomy approval is sought. For activities which go beyond 2050, it must be technically feasible to reach net-zero emissions.

As it can be noticed looking at Table 7, for different technologies the threshold is set on life cycle emissions. Nevertheless, in TEMOA-Italy database such information are not provided, therefore checking such threshold was not trivial at all. Looking at the graph below (Figure 8), made by UNECE (United Nations Economic Commission for Europe) [56], it comes out that wind power technologies can be considered eligible. For hydro, it can be deduced that the new technologies in the TEMOA-Italy database have life cycle emissions below the limits imposed by the Taxonomy as they are mini and micro hydroelectric and therefore fall into the first category shown in the graph, i.e., the range between 6.1 and 11 gCO2eq per kWh envisaged for an installed capacity of 360 MW. The range is wider for solar PV, but it seems reasonable to assume the eligibility for these technologies as well.

Since the observed values, except for solar PV, are already well below the current Taxonomy limit, it is reasonable to assume that by 2050 they will reach 0 gCO2eq per kWh. This assumption has also been made for solar PV, although this technology would deserve a separate discussion, which, however, it is not straightforward to do because of the lack of clear and unambiguous data on the carbon footprint of PV panels imported in Europe and, mostly, in Italy.

Finally, for technologies using natural gas, both with and without CO2 capture, it is evident that values are well above the 100 gCO2eq per kWh set by the Taxonomy. In fact, a check was performed for all power technologies using natural gas, and, only for the emissions due to the operation of the power plant – as this information is available on TEMOA-Italy database –, the values were always above the threshold set in the TSCs, even in 2050.

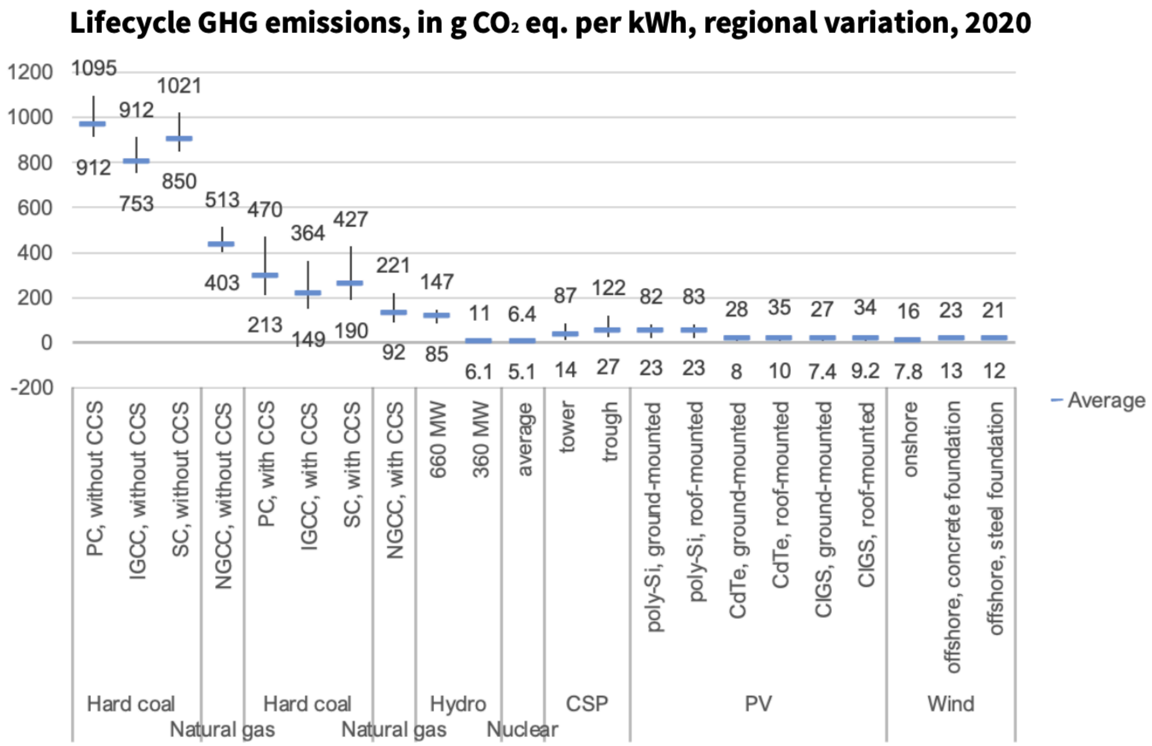


Figure 8. Lifecycle GHG emissions, in g CO2 eq. per kWh, regional variation, 2020 [56].

Concerning cogeneration plants, it was not possible to calculate the Weighted Cogeneration Threshold since it requires knowing how much electrical and thermal power are typically produced by the plant itself. In the TEMOA-Italy database, instead, the cogeneration plants are modelled using average parameters representative of the technologies available on the market. Therefore, given that in TEMOA-Italy for each type of cogeneration plant it is possible to trace the fraction of electricity and heat produced by looking at the *TechOutputSplit* and *TechInputSplit* parameters, it was decided to calculate the Weighted Cogeneration Threshold as a weighted average between the expected threshold for electricity (i.e., 100 gCO2e/kWh declining to 0 gCO2e/kWh by 2050) and the expected threshold for heat (i.e., 30 g CO2e/kWh, declining to 0 g CO2e/kWh by 2050).

4.3.2. From the EU Taxonomy mitigation Technology Screening Criteria to the TEMOA-Italy sectors

The scheme below simply resumes the following steps of integration of the Taxonomy TSC within the methodology. The Python script developed, namely *taxonomy.py* [54], takes as input the hurdle rate values evaluated by the script explained in the section 4.3.1, data about the technologies from the database under investigation and all the EU Taxonomy threshold values to be considered. If the efficiency or the *EmissionActivity* (i.e., a parameter used in TEMOA to account for emissions per unit of activity) value of a technology (or both in some cases) fulfils the EU Taxonomy requirement, a premium is assigned and vice versa and, afterwards, the hurdle rates values are updated. It is important to remark that, as done for the hurdle rate evaluation, the TSC thresholds were uniquely associated with the goods or services they refer to – and in some cases also to the input commodity needed as for hydrogen storage, electric heat pumps, power plants and decentralised heat and power systems –, rather than with the technologies themselves, within a separate table contained in a .csv file [54].

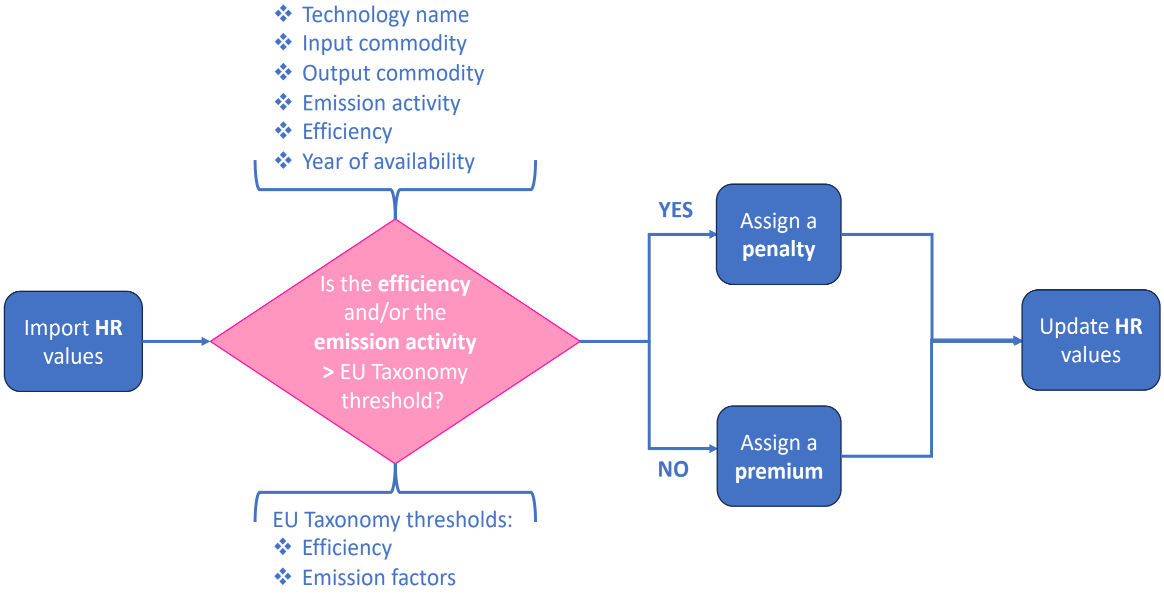


Figure 9. A simplified scheme of the taxonomy.py script

Before analysing the code in detail, it is essential to point out that it interacts with the TEMOA-Italy database after the interpolation and extrapolation, in order to have the properties like the efficiency or the emission activities defined per each year of the time horizon [9] . This is done because both the properties of the technologies and certain thresholds imposed by the taxonomy vary up to 2050. For several technologies in TEMOA-Italy, efficiency and emission factors increases and decreases over time, respectively. Clearly, the evolution of all techno-economic parameters that characterises the technology stock is known a priori, in compliance with the perfect foresight approach adopted in ESOMs. Therefore, it is fundamental to take into account the possibility that a technology, from 2025 (i.e., the year on which the taxonomy was chosen to start) onwards, may become eligible later on, due to an improvement in terms of efficiency or emission activity or vice versa, it may become non-eligible due to a tightening of thresholds (see Table 7).

Starting from the emission activities, information such as technology name, input commodity, output commodity, emission activity and the year to which they relate were imported from the table *EmissionActivity* [38]. The emission activity is given for each type of GHG emitted and in terms of equivalent emissions of CO2 too per unit of activity produced – where the activity can comprehend multiple outputs (see Table 8), while the emission thresholds set by the Taxonomy are given in terms of quantity of CO2 (or CO2 equivalent) per unit of the output under investigation (i.e., tons of a good produced, kWh of electricity). In particular, as technologies can have multiple inputs and outputs, the values of emission activity are provided per each pair of input and output commodity.

Table 8. Example of EmissionActivity given for the technology producing Basic Oxygen Furnace (BOF) steel with CCS [37].

Input Commodity	Technology	Output Commodity	Emission Activity	Unit
Blast furnace gas	BOF steel production with CCS	Blast furnace gas	405.6	[kt/act]
Blast furnace gas		BOF steel	405.6	[kt/act]
Coal		Blast furnace gas	76.6	[kt/act]
Coal		BOF steel	76.6	[kt/act]

Indeed, the total emission factor was evaluated as a weighted average according to the following formula:

$$Total\ EmissionFactor\left[\frac{ktCO2(e)}{Output_j}\right] = \frac{1}{TechOutputSplit_j} \cdot \sum_{i=1}^{N} EmissionActivity_i \cdot TechInputSplit_i \cdot TechOutputSplit_i \tag{11}$$

Where:

- j is the index referred to the output commodity under investigation
- i is the index referred to the input commodities used by the technology
- *TechOutputSplit* is a parameter that fixes the minimum shares of output commodity (with respect to the total output commodity flow) for a specific technology in a given period
- *TechInputSplit* is a parameter that fixes the minimum shares of input commodity (with respect to the total input commodity flow) for a specific technology in a given period

- *EmissionActivity* is the emission activity related to the ith pair of input and output commodities in the given period

Therefore, for the technologies whose output was mentioned by the EU Taxonomy in terms of emission factors, the values of *TechInputSplit* and *TechOutputSplit* were taken per each input and output commodities from the respective tables.

As it can be seen from the figure below, the total emission factor was evaluated only for the technologies whose output commodity is associated with an emission factor threshold within the EU Taxonomy. Such emission factor could be referred only to CO2 emissions or to GHGs emissions. Afterwards, the difference with the threshold was evaluated and an emission premium or penalty flag was assigned.

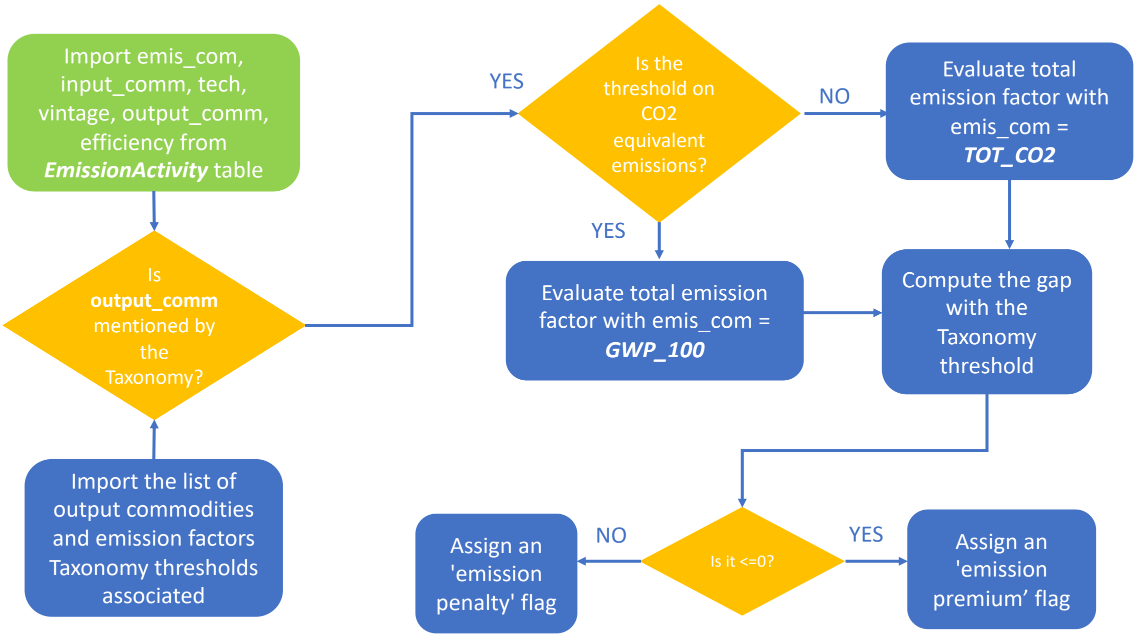


Figure 10. Scheme of the integration of the EU Taxonomy thresholds on emission factors

As for efficiency, most of the thresholds mentioned by the EU Taxonomy concerns the electricity consumption of some industrial processes (i.e., manufacture of aluminium, inorganic basic chemicals and hydrogen). In TEMOA-Italy, whether it comes to technologies having multiple inputs and outputs, for each pair of input and output a value of efficiency is provided. Thus, the total electricity consumption of a certain technology was evaluated according to the following formula, in order to consider also the electricity consumed by outputs not mentioned by the Taxonomy but produced by the technology under investigation:

$$Total\ Elc\ Consumption \left[\frac{MWh}{Output_i}\right] = \frac{1}{TechOutputSplit_i} \cdot \sum_{j=1}^{N} \frac{1}{Efficiency_{ELC \to Output_j}} \cdot TechOutputSplit_j \qquad (12)$$

Where:

- i is the index referred to the output under investigation
- j is the index referred to the number of output commodities used by the technology
- *TechOutputSplit* is a parameter that fixes the shares of commodity output to a specific technology in a given period
- $Efficiency_{ELC?Outputj}$ represents the quantity of output produced per unit of electricity used.

Also in this case, for those technologies to which the taxonomy assigned a control on electricity, the *TechOutputSplit* was taken to calculate the total electricity consumption.

In this code also the technologies eligible by default (i.e., rooftop solar PV modules, solar hot water panels, solar transpired collectors) were considered, while for the power sector a function was created since, as stated previously, the emission thresholds vary according to the type of fuel involved.

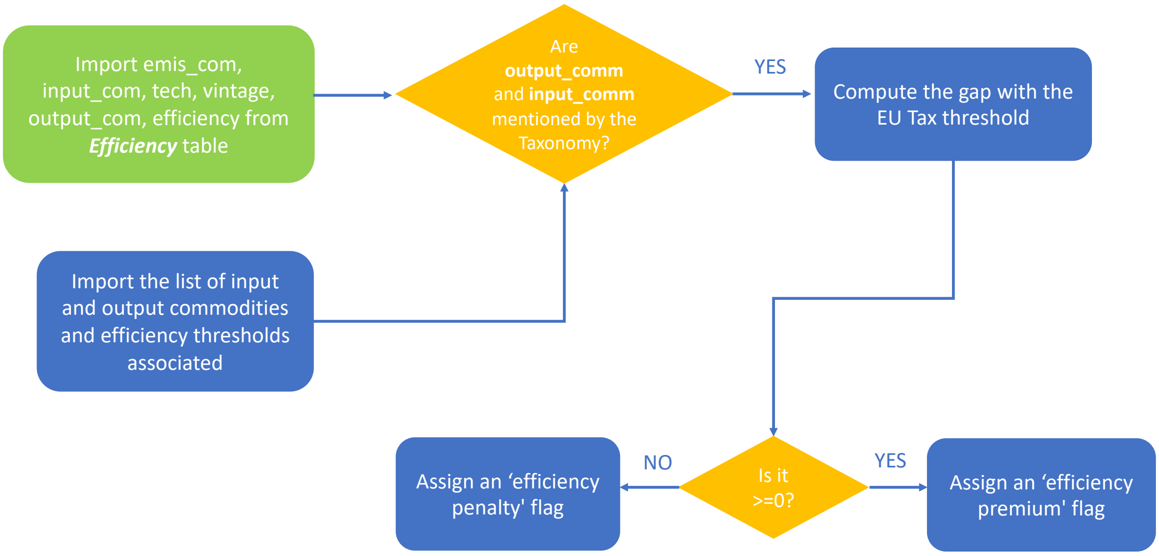


Figure 11. Scheme of the integration of the EU Taxonomy thresholds on efficiency

The rationale-behind this scheme (see Figure 11) is the same applied for the emissions.

Afterwards, in the last part of the *hurdle_rate.py* [54] script, efficiency and emissions flags were checked: in fact, for technologies with a threshold on both, both criteria must meet the Taxonomy to be eligible. Finally, the flag is turned into a numerical value representing the premium/penalty and the hurdle rate values were updated in the *DiscountRate* table. In turn, the updated database provided input data to the solver.

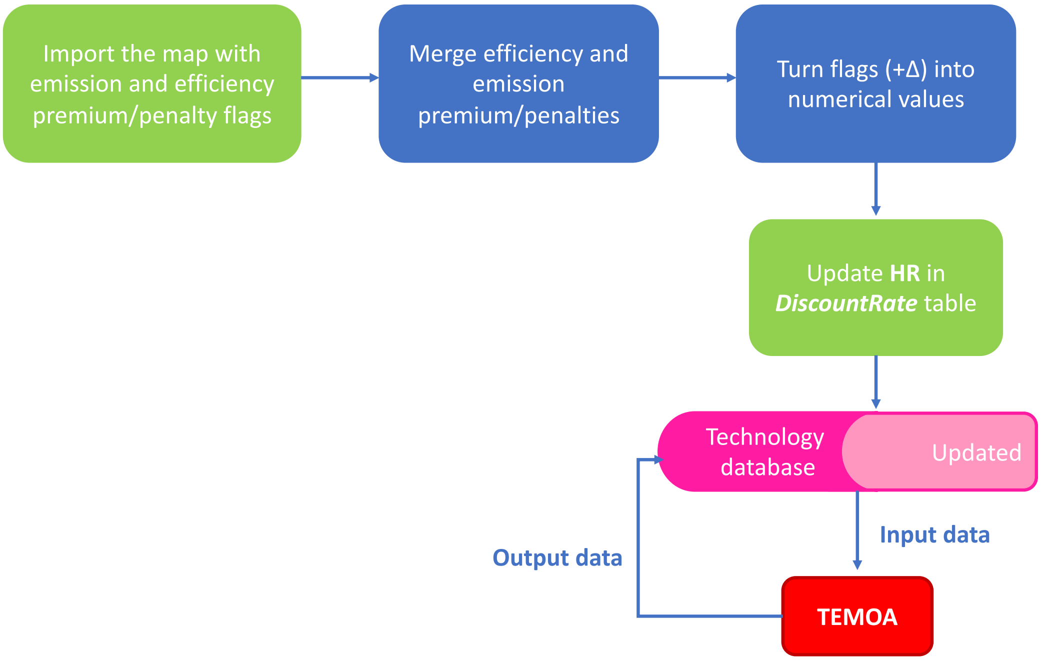


Figure 12. Scheme of the assignment of premia and penalties and update of the TEMOA-Italy database.

The figure below summarizes the role played by the codes implemented in this work. Indeed, the first code, namely *hurdle_rate.py* [54] and described in section 4.2.2, received input the TEMOA-Italy technology database and the database containing economic parameters for the evaluation of the hurdle rate. The *taxonomy.py* [54] code, instead, imports the technologies characteristics from the TEMOA-Italy database to be checked in accordance with the EU Taxonomy thresholds on mitigation criteria and, consequently, the value of hurdle rates is then updated. Finally, the updated TEMOA-Italy database is the input for the optimization solver.

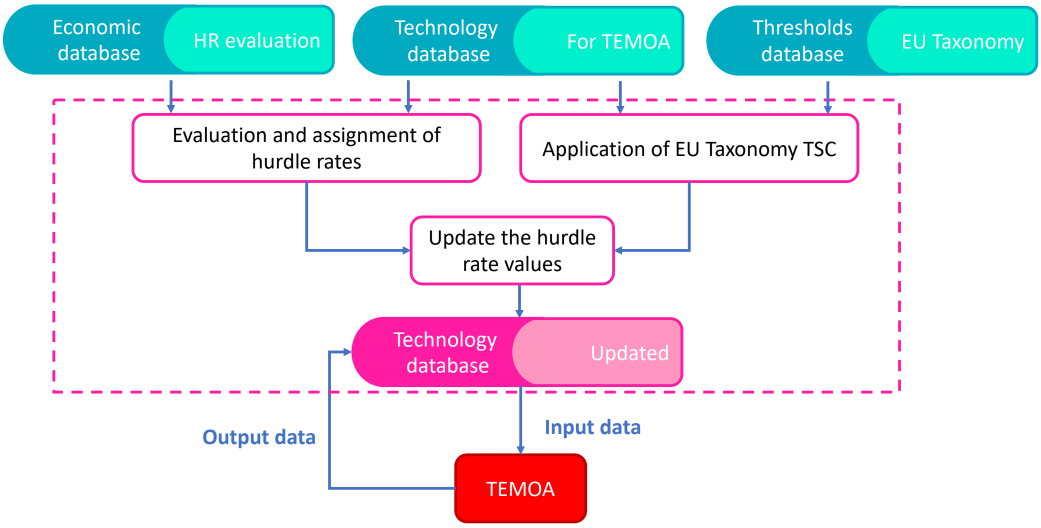


Figure 13. Simplified scheme of the overall methodology.

4.3.3. The nexus between the hurdle rates and the EU Taxonomy

Finally, it is important to specify why the outcome of the comparison with the thresholds set by the EU Taxonomy increases or decreases the hurdle rate.

The EU Taxonomy may represent a policy risk for brown investments as it enables the clear recognition of clean investments and, in turn, the scaling up of sustainable investments [3]. As explained in section 2.1, policy risks are among those accounted for the hurdle rate evaluation. It seems reasonable to translate the impact of the EU Taxonomy in a quantitative way, thus assuming that it affects hurdle rates by decreasing the hurdle rate of sustainable technologies and vice versa for non-eligible technologies. In particular, in [57] it has been estimated that the introduction of a green supporting factor for capital reserve requirements in the EU would lead to a reduction of the WACC of 5 to 26 basis points for green projects (with inverse expected effects for a brown penalty). Therefore, such values have been considered in this work to respectively increase or decrease the WACC – and so the hurdle rate – of a brown or green investment.

5. Results

5.1. The studied scenarios

The methodology developed was then tested by implementing different scenarios. First, the objective was to assess the impact of the hurdle rates in TEMOA-Italy sectors. Consequently, a comparison was made between a scenario based on the few hurdle rates present in the previous version of the TEMOA-Italy database and a scenario based on the methodology developed to evaluate the hurdle rates.

Afterwards, the impact of the EU Taxonomy was investigated by comparing different types of decarbonisation scenarios. In particular, the emission limit set for 2030 (see Table 9) is compliant with the target of reducing CO2 emissions by 55% as to the 1990 level [58]. Whereas the value to be reached in 2050 is in accordance with the Italian Long-Term Strategy on the Reduction of Green House Gases Emissions [58]: in fact, it states that climate neutrality could be achieved if the reduction the sectorial emissions – including also CCS technologies – arrive at around 40-50 Mtons of CO2, equivalent to the maximum capacity assumed for the Land Use, Land Use Change and Forestry (LULUCF).

Finally, the focus was moved towards the social discount rate. Although a methodology to calculate it was not developed in this work, understanding its effects, and how it combines with the hurdle rate is a starting point for subsequent analyses.

In particular, while the default value usually adopted is 5%, in this work a value of 3.7% was adopted too, in compliance with what was proposed by a research work focusing on Italy [59].

Table 9. An overview of the studied scenarios

			BASIC	**HR (SDR 5%)**	**BAU w/ Taxonomy (26 bps)**	**NZE w/o Taxonomy**	**NZE w/ Taxonomy (5 bps)**	**NZE w/ Taxonomy (26 bps)**	**SDR 3.7**
Definition			Scenario based on few hurdle rate values present in the previous version of TEMOA-Italy database.	Scenario based on the methodology developed in this work to evaluate the hurdle rates.	BAU (Business-As-Usual) scenario in which the methodology developed in this work to evaluate the hurdle rates is combined with the EU Taxonomy scheme. A premium/penalty of ± 26 bps is assigned.	Decarbonisation scenario in which the methodology developed in this work to evaluate the hurdle rates is applied.	Decarbonisation scenario in which the methodology developed in this work to evaluate the hurdle rates is combined with the EU Taxonomy scheme. A premium/penalty of ± 5 bps is assigned.	Decarbonisation scenario in which the methodology developed in this work to evaluate the hurdle rates is combined with the EU Taxonomy scheme. A premium/penalty of ± 26 bps is assigned.	Scenario in which the global discount rate is set at 3.7%. The hurdle rates are evaluated through the methodology developed in this work.
Hurdle rates			TEMOA-Italy previous database	Methodology	Methodology ± 26 bps	Methodology	Methodology ± 5 bps	Methodology ± 26 bps	Methodology
Social discount rate			5%	5%	5%	5%	5%	5%	3.7%
Constraints	Total CO2 [Mton]	2030	None	None	None	226	226	226	None
		2050	None	None	None	36	36	36	None

5.2. The impact of the hurdle rates

First, the impact of the hurdle rates was investigated in all the sectors. It is important to specify that hurdle rates were applied for all the years in which new technologies are available, thus including the historical period. When analysing the results, comparing the scenarios also in the past future years allowed us to validate the results obtained with the new database since the model was already calibrated to be consistent with the historical data.

As expected, the sectors for which no hurdle rates were defined (i.e., agriculture, buildings and commercial) did not undergo any notable changes, except for the upstream sector, which is inevitably affected by changes in the other sectors in terms of fuels required, as will be described more in details in the transport sector result part.

Looking at the power sectors, instead, some interesting remarks can be made. When hurdle rates are added, the share of renewables in the electricity mix tends to be at least 3 percentage points lower in the period 2022-2050, as depicted in Figure 14. This is not a huge value, but it is consistent with the hurdle rate definition, and with what has been observed in the other research [12], where scenarios where higher hurdle rates were used tended to have a lower renewable contribution. The higher the hurdle rate, the higher the annual payments spread over the lifetime of an investment and consequently the higher the total cost. That is the case when moving from the BASIC scenario with hurdle rates equal to the global discount rate of 5%, to the HR scenario with higher hurdle rates. For what concerns the historical years, instead, no remarkable differences were detected between the two scenarios due to the calibration performed to make them compliant with the actual historical electricity mix.

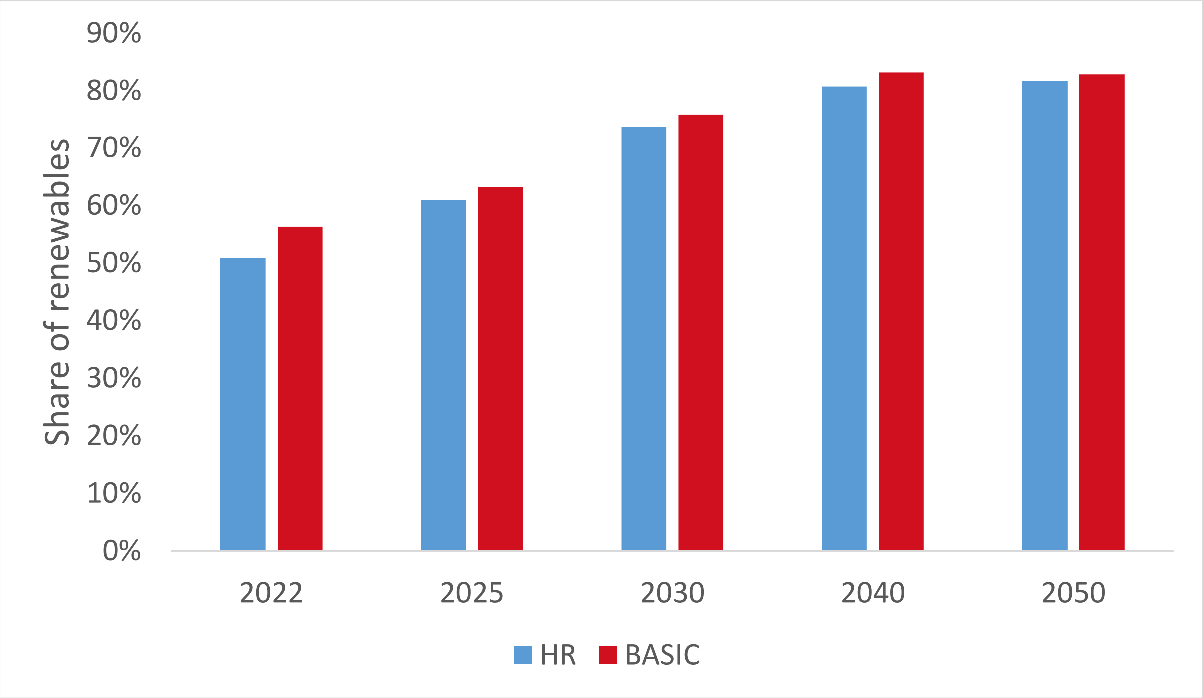


Figure 14 Share of renewable energy sources in the electricity mix as computed by TEMOA-Italy

For what concerns the centralised heat production, instead, values look quite different. The total centralised heat production is higher in HR than in BASIC scenario reaching an increase of 20% in 2007 (see Figure 15).

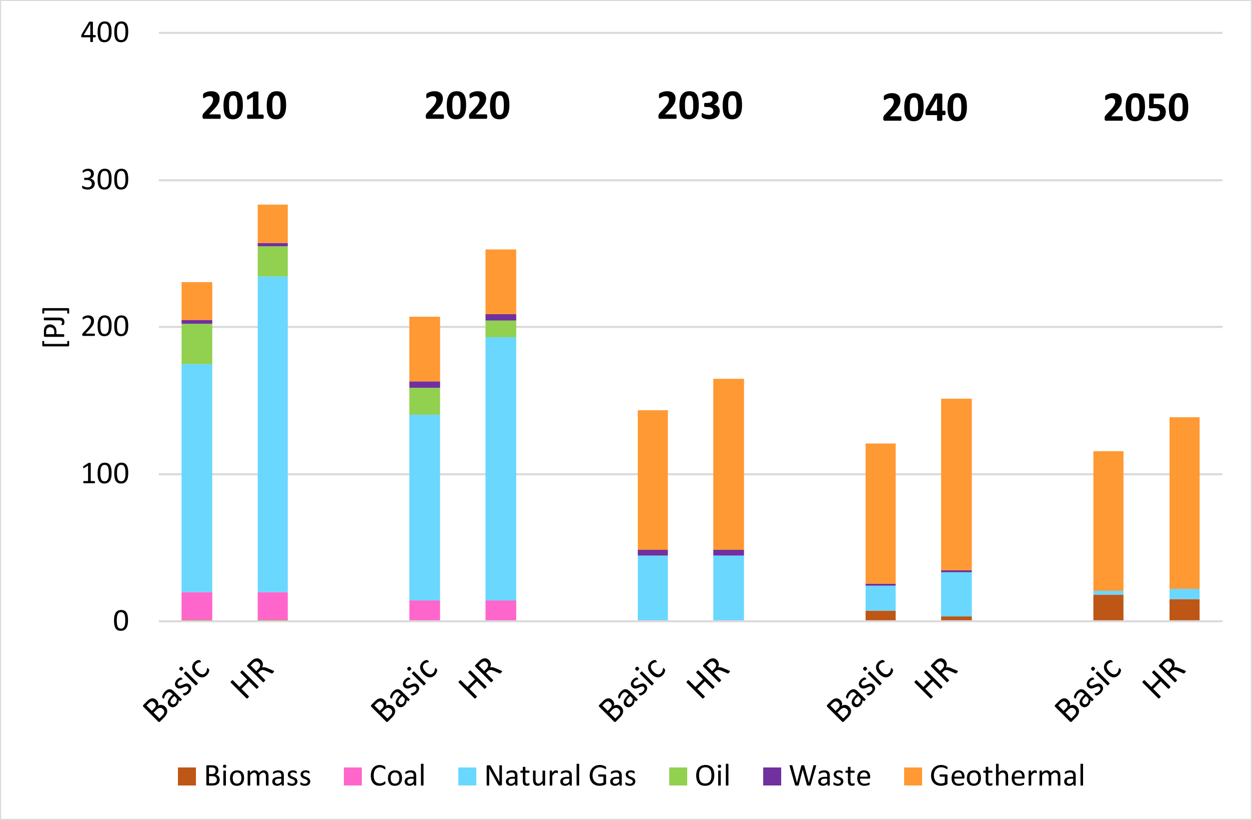


Figure 15 Energy consumption for centralised heat production by fuel in BASIC and in HR scenario

Such difference can only be explained by looking at the decentralised heat production that takes place in combined heat and power (CHP) plants, mainly in the industrial sector.

In fact, while the decentralised production is higher in BASIC (and vice versa for centralised production), the total heat production, on the other hand, remains unchanged due to the calibration performed in the historical period, as it can be seen from the green line in Figure 16. The discrepancy that exists between the two scenarios in terms of decentralised production is due to the fact that these technologies (e.g. internal combustion engine fed by bioliquids or natural gas) were assigned a hurdle rate of 10%, which, while being equal to that of the centralised technologies that the model prefers to install and use, is double the default 5% value it has in the BASIC scenario. Comparing the two blue areas, however, it comes out that this distinction diminishes going towards 2050, since 60% of the number of centralised CHP plants was already existing at the base year (2006) and by 2040 they all have been shut down, so, regardless the higher hurdle rate, new industrial CHP were installed during the last 10 years also in the HR scenario.

It is important to specify that, even if CHP plants also produce electricity, all the above-mentioned differences had a higher impact on the centralised heat production than the electricity one as the former is much lower in absolute value than the latter. In fact, throughout the time horizon, the amount of centralised heat produced equals around 10-20% of the centralised electricity production.

Another interesting remark can be made by looking at the historical values of decentralised production. In fact, by comparing the two scenarios with the actual historical trend [60] represented by the red line, it comes out that the market evolved with numbers more similar to the BASIC scenario than the HR one, in a way that can only be considered optimal if the risks associated with new technologies are not fully considered, something on which the HR scenario is more rigorous. Furthermore, the results between the two scenarios differ so much because the TEMOA-Italy model is constrained through the calibration in terms of sectorial consumption – and in turn production – of heat, but not in terms of technology choice between centralised and decentralised plants.

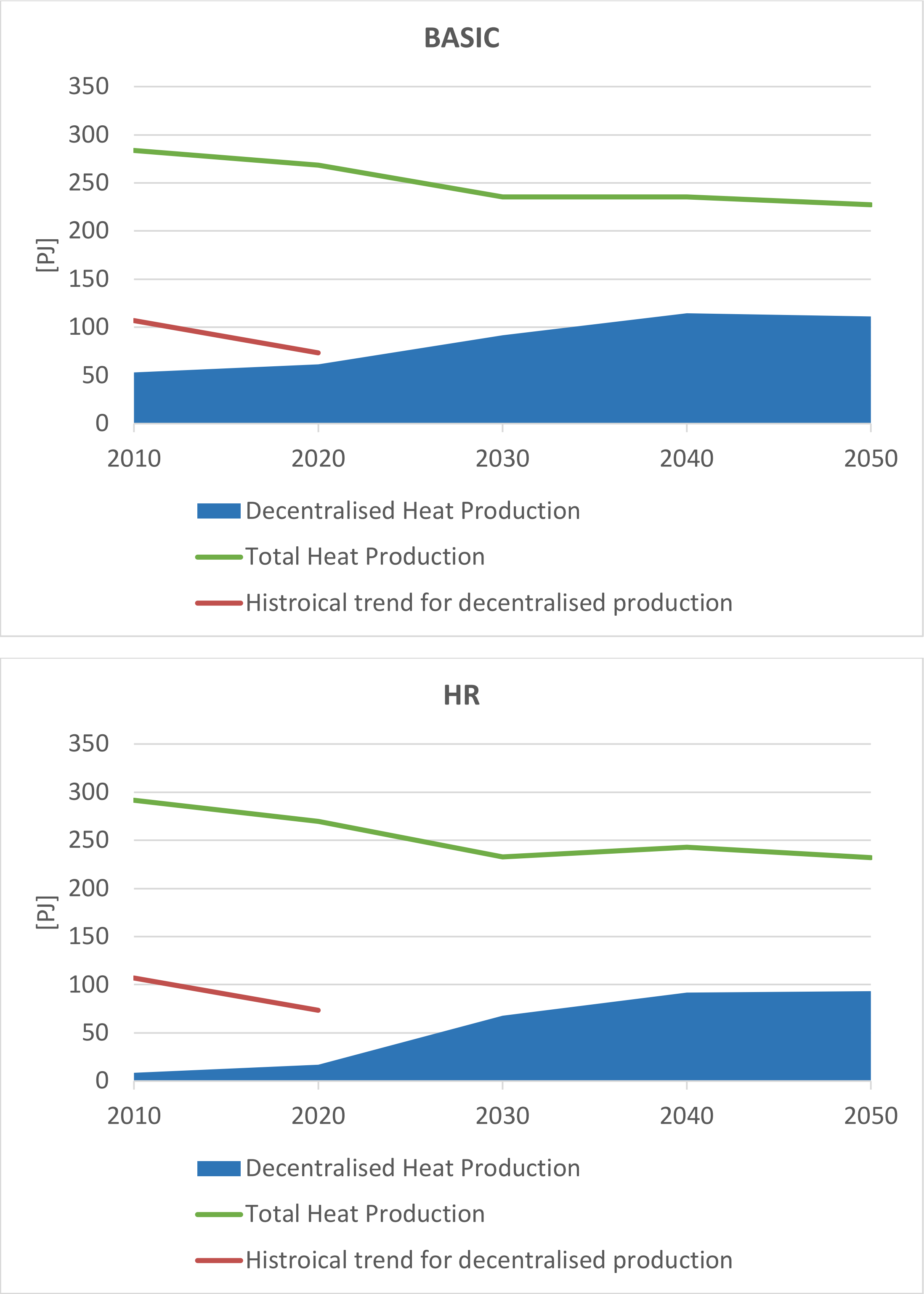


Figure 16. Evolution of centralised and decentralised heat production in BASIC scenario (a) Evolution of centralised and decentralised heat production in HR scenario (b)

Looking at the fuel consumption in the transport sector, instead, the two scenarios show almost the same evolution, except for diesel consumption, which is higher in the BASIC scenario by 5%, 10% and 5% in 2030, 2040 and 2050 respectively (see Figure 17). Whereas in BASIC, hybrid heavy trucks (powered 55 per cent by diesel and the remaining 45% by electricity) covered almost the entire demand by 2050, in the HR scenario, as this technology (as well as fully electric heavy trucks) is assigned a hurdle rate of 24%, diesel-only heavy trucks tend to prevail, which have a hurdle rate of 6 per cent, and the use of hybrids decreases, as it can be seen from Figure 18). Therefore, when the model has to install and use new technologies in the future, it opts for the ones with a lower discount rate. Moreover, this effect is also propagated in the upstream sector where the HR scenario has a 5% higher import of oil for refining than the BASIC scenario.

Figure 17 Diesel consumption in the transport sector in BASIC and in HR scenario

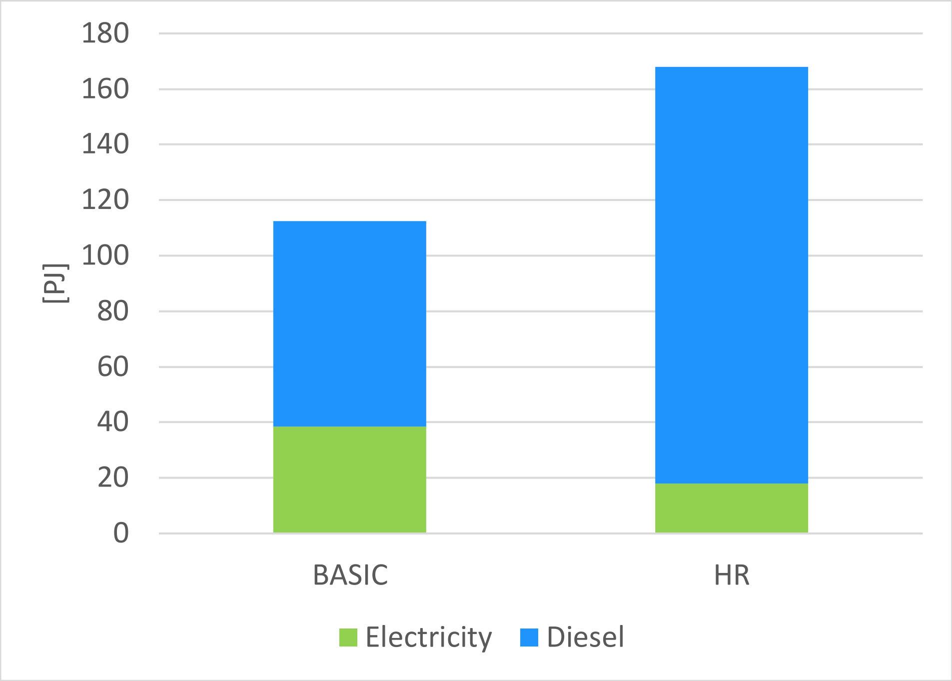


Figure 18. Fuels used in heavy truck transport in 2050.

Summing up, hurdle rates do not affect the results remarkably and, except in some cases when the technologies hurdle rates differ significantly, as shown in the transport road sector, they do not always play a key role in the choice of technology. Indeed, it must be considered that other factors come into play in the objective function (e.g., fixed and variable operational costs). Nevertheless, hurdle rates enrich the analysis by accounting for risks related to new projects and technologies.

5.3. The impact of the EU Taxonomy

The analysis was then moved towards the assessing of the impact of the EU Taxonomy. As a first trial, a premium/penalty of 5 bps was assigned, but no differences were found with respect to the HR scenario. Indeed, even applying a value of 26 bps the results did not change noticeably. This outcome should come as no surprise since only 5 or 26 bps were added to a parameter that it has already turned out not to be so decisive in the choice of technology and, furthermore, as stated in [57], an adjustment of 5-26 basis points of the WACC is not likely to fundamentally change the financing conditions of green assets.

Nevertheless, it is interesting to investigate how this scheme would fit with a decarbonisation scenario, whether it can foster somehow the deployment of clean energy investment or not. Therefore, the EU Taxonomy approach, assigning a premium/penalty of 5 bps and then 26 bps, was combined with the emission targets by 2030 and by 2050 explained in Table 9.

As the Taxonomy was applied to new investments starting from 2025, the cumulative investment cost in the period 2025-2050 were analysed (Figure 19).

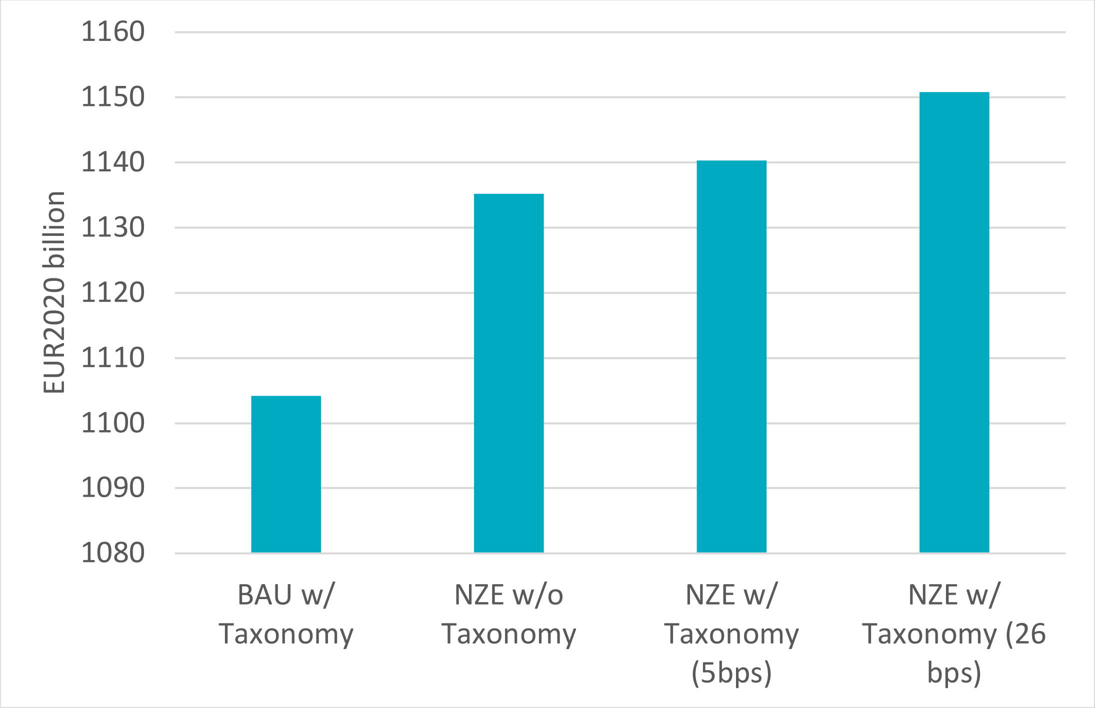


Figure 19. Cumulative investment costs, period 2025-2050.

As expected, the decarbonisation scenarios are always more expensive than the BAU one. In particular, the gap between the decarbonisation scenario without Taxonomy and the BAU is around EUR 35 billion and it decreases by including the Taxonomy scheme, so that, in the case of the NZE with Taxonomy (26 bps), the system costs EUR 50 billion more than the BAU scenario.

Basically, by comparing Figure 20 and Figure 19, it comes out that clean investments represent only 1/10 of the total investments. This is because the optimization process chooses mainly technologies not considered green by the Taxonomy, despite the scheme reducing the cost of clean energy solutions.

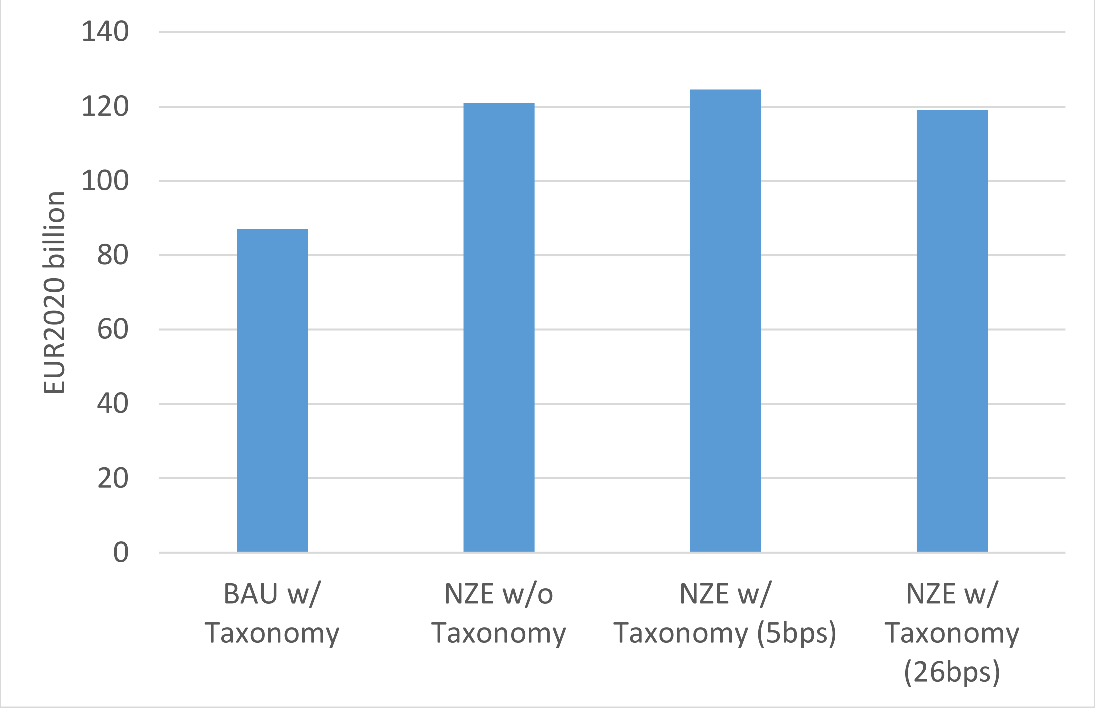


Figure 20. Cumulative clean investment costs, period 2025-2050.

For instance, in all decarbonisation scenarios, the production of synthetic diesel – which is not considered eligible by the Taxonomy – reaches around 800 PJ in 2050, allowing hybrid and diesel cars to cover 70% of the demand for passengers' cars in 2050, while the rest is still using gasoline. Therefore, the model decides to use diesel and gasoline – having a hurdle rate of around 6% - rather than installing the only type of car, which is considered eligible by the Taxonomy, namely the EVs which have a hurdle rate of 24%. For the model, this difference weighs more than the fact that the hurdle rates of technologies producing hydrogen and synfuels are higher than those of technologies producing electricity for EVs.

It is worth mentioning that these results contrast with several announced policies based on the fact that decarbonisation targets can be achieved by increasing the share of renewable energy produced on the supply side while ensuring a significant rate of electrification of end-use sectors (e.g., by deploying EVs). In fact, while for the European Commission [61], all new cars and vans registered in Europe will be zero-emissions by 2035, in April 2022 the Italian government announced that EUR 650 million will be devoted in the years 2022-2023-2024 to incentivise the purchase of electric cars and motorcycles [62]. Therefore, results more in line with electrification targets might be achieved by further considering incentives campaigns, government grants for charging infrastructure as well as vehicle taxation and duties.

Summing up, the fact that the Taxonomy does not lead to a decisive shift towards clean technologies is not at all shocking. In the first place, it is a scheme that provides quantitative criteria to distinguish sustainable from non-sustainable investments and not an incentive mechanism with precise targets as mentioned above. Secondly, it all depends on how one decided to implement the Taxonomy within the mode, that is, in this work, through, a tool that increases or decreases the hurdle rate of technologies by a maximum of 26 basis points. At the end, regardless of the value assigned to this premium, the model always chooses the cheapest solution.

5.4. The impact of the social discount rate

Finally, the role of the social discount rate was investigated.

Usually, the lower the social discount rate, the higher the renewable contribution [12]. Nevertheless, the only sector in which this phenomenon is noticed is the commercial one. In fact, in 2050, while natural gas consumption decreases by 11%, the consumption of solar energy increases by 41% (see Figure 21). In particular, the model opts for more expensive space-heating solutions based on solar energy rather than natural gas.

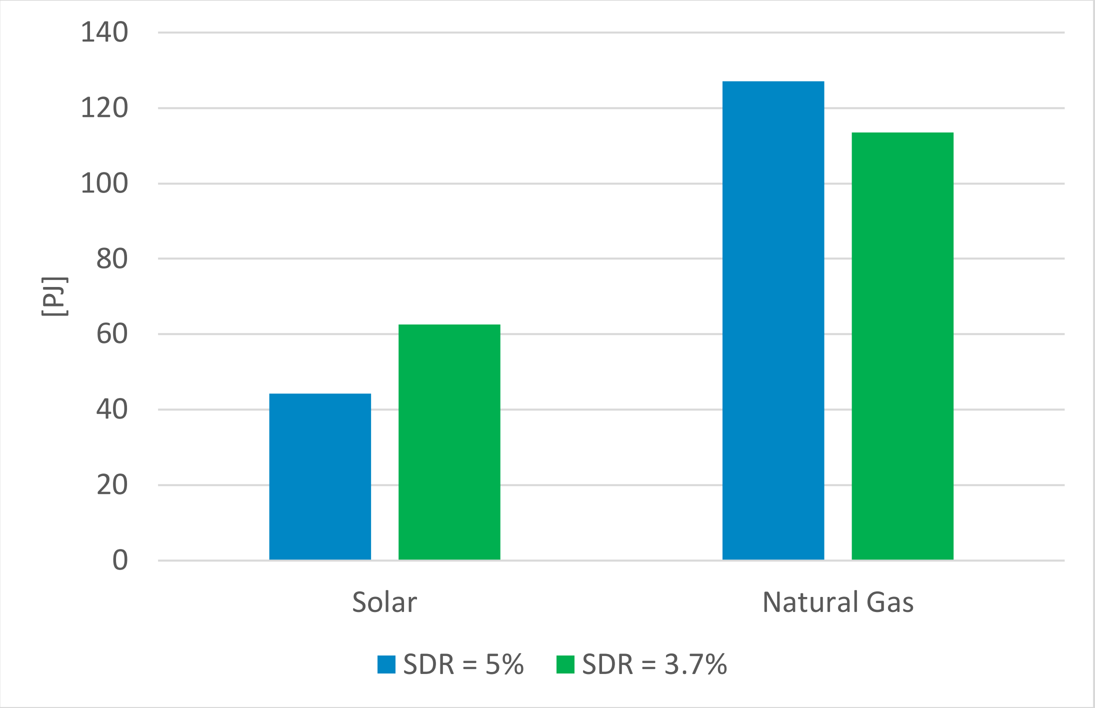


Figure 21. Fuels consumption in commercial sector in 2050

It is evident that further investigations are needed to fully comprehend the role of the social discount rate. On the same time, in this work, it was decided to do not to make any rash assumptions about its value, and considering that the literature for European nations recommends not using a value above 4-5% in ESOMs [12], it can be said that the range of action for freely modifying this parameter was rather small.

6. Conclusions and perspective

This work had the aim to develop a clear methodology to evaluate the hurdle rates of the technologies typically composing the Reference Energy Systems of ESOMs.

First, the role played by hurdle rate in ESOMs was investigated, as well as the state of the art in the ESOM literature and the research gaps still present. Once the methodology was identified, it was implemented only for those sectors for which it was possible to find the values of the economic parameters on which the hurdle rate depends, i.e., industry and transport. Alternatively, for sectors such as power generation, in the absence of available data on economic parameters such as beta or debt-to-equity ratio, hurdle rate values assessed by third parties were taken. Nevertheless, having developed the methodology for the evaluation of the hurdle rates within an open-source framework allows to share it with the community of modellers, paving the way to integration, discussions, and updates, especially for the values that still rely on third parties' guesses. In addition, it is important to remark that, even if the methodology was applied to the TEMOA-Italy model, the rationale-behind it is valid for each ESOM.

Afterwards, the EU Taxonomy criteria used to determine whether a technology is sustainable were integrated in the methodology. Depending on the result of the comparison between the limits set by the EU Taxonomy and the characteristics of the technologies, their hurdle rate was lowered or increased, since this scheme can potentially foster the deployment of sustainable activities and, respectively, disincentivise the money flows towards brown investments. In addition, the methodology could be easily combined with other policy schemes, thus allowing to investigate in a flexible way the impact of different schemes on costs. In fact, changing the values of the Taxonomy premium/penalty or assigning a new social discount rate was trivial as there was no need to create a new database for TEMOA-Italy, but just to update a few parameters of the database in which properties are already extrapolated or interpolated.

The impact of the hurdle rates and of the EU Taxonomy application were then investigated by implementing several scenarios.

The energy mix evolution obtained with the TEMOA-Italy database integrated with the methodology were compared with the one obtained with the previous version of the model which contained only a few hurdle rates for the power sector. Even if hurdle rates did not affect the results significantly, in some cases they played a role in the technology choice. In fact, it was observed in some sectors that the higher the hurdle rates, the lower the renewable contribution. In any case, they allow to enrich the analysis by including risks not accounted previously.

The analysis was then moved towards the assessing of the impact of the EU Taxonomy. By applying a premium/penalty of both 5 bps and 26 bps no differences were found with respect to the HR scenario. In turn, the role of the EU Taxonomy scheme within a decarbonisation scenario was analysed. It came out that, even if the EU Taxonomy lowers the hurdle rates – and so the capital cost – of the clean technologies, the model still opts for solutions that are not considered sustainable by the EU Taxonomy, as they are cheaper. Therefore, in order to foster the investments in clean activities, more policy incentive schemes are needed or, alternatively, the EU Taxonomy might be modelled in a different way.

Furthermore, in perspective of extending this research, a look was also taken at the effect that social discount rate has on outcomes. In particular, it was observed that the lower the social discount rate, the higher the renewable contribution.

Nevertheless, it is worth to mention that this methodology is still at an early stage and different aspects needs to be further analysed. The residential and commercial sectors should be included as well, in such a way that risks related to consumers' behaviour (e.g., bounded rationality and lack of knowledge) may be considered.

As for the EU Taxonomy, instead, the criteria neglected so far need to be included in the analysis. In particular, a parameter to consider the emissions related to the supply chain of specific technologies could be added, thus allowing to properly evaluate the Taxonomy thresholds related to life cycle emissions. Indeed, the simplification made so far for the power sector (i.e., by assuming that life cycle emissions correspond to the emissions vented during the plant operation) may underestimate the impact of extraction, manufacture, and transport processes for some technologies, such as solar PVs. Furthermore, the TSC on the average carbon intensity of the electricity used in some industrial processes (e.g., hydrogen or aluminium production) have highlighted another aspect, that is the possibility to have parameters depending on the result of the optimization process. Indeed, the hurdle rate should therefore go from being a simple number given as input to being endogenized. In turn, making TEMOA-Italy able to deal with non-linearity like this could pave the way for modelling other dynamics of the energy systems.

Finally, in a next step, the social discount rate is likely to be analysed in more depth, in order to identify a methodology that allows it to be evaluated also and above all in the light of the different policy schemes that are implemented.

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