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No. S05/2025

Publishing Notes

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Cover page: Shutterstock.com/TechSolution

Recommended citation

Berger, F.; Suerkemper, F.; Kaselofsky, J.; Vondung, F.; Swagemakers, J.; Reinfandt, N.; Eichhammer, W.; Wagner, F.; Kokkinos, C.; Andreou, A.; Eidelloth, S.; Ellmauer, C.; Lorenz, T. (2025): A comprehensive multiple impacts framework to assess decarbonisation measures. DOI: 10.24406/publica-6890

Published

December 2025

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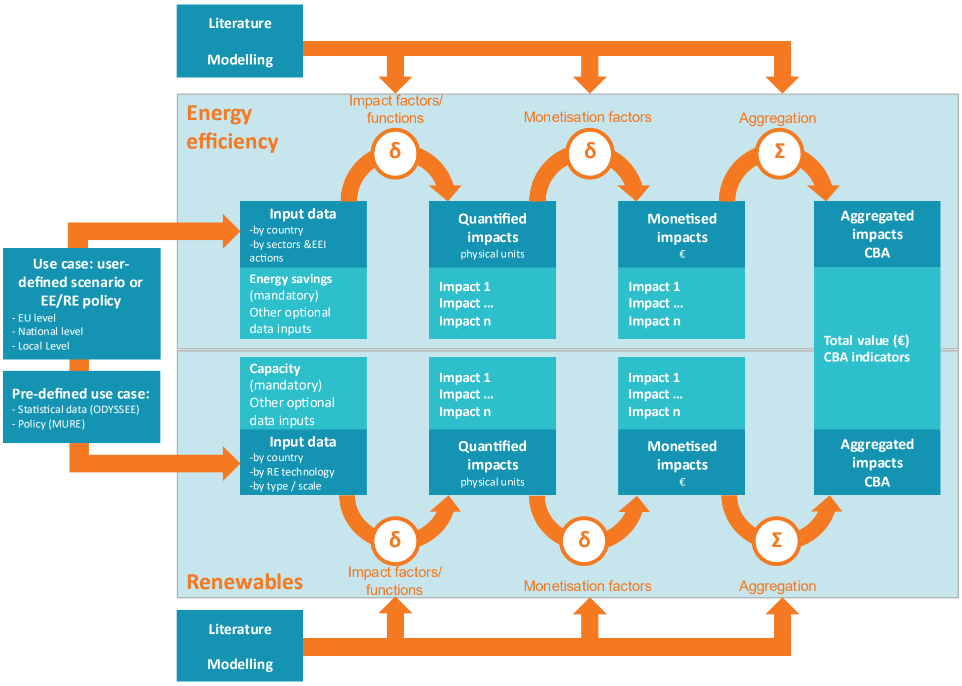
Notes

Abstract

The MICATool is a comprehensive framework designed to assess the Multiple Impacts of energy efficiency and renewable energy measures. Its methodology allows the incorporation of a variety of social, economic and environmental indicators reflecting the wider impacts of assessed measures. The framework provides the necessary inputs and gathers indicators' results, in both physical and, where applicable, monetised terms. Furthermore, the results can be assessed in a cost-benefit analysis module. As a result, the MICATool supports the assessment and comparison of different measures pertaining to energy efficiency and renewable energy.

- The framework allows for the embedding of multiple impact indicators for quantification and monetisation
- These assessments allow for better informed energy policy decisions

Figure 1: Graphical abstract



Acknowledgements

We want to thank all project partners of MICAT and SEED MICAT for the support in developing this methodology and the associated MICATool. Moreover, we want to thank the many people having tested the tool in its early stages, pointing us to remaining inconsistencies and bugs.

This research was carried out in the framework of the EU Horizon 2020 project MICAT (Grant agreement nr. 101000132) and its follow-up EU LIFE project SEED MICAT (project ID 101120599).

Contents

1 Background

Several quantification approaches have been developed for assessing the multiple impacts (MI) of energy efficiency (Campbell et al. 2015; Reuter et al. 2020; Ryan und Campbell 2012; Thema et al. 2019), with some also addressing the impacts of renewable energy (Makešová und Valentová 2021; Breitschopf et al. 2016; Sovacool et al. 2021; Resch et al. 2016). These approaches are often based on complex modelling techniques or rely on indicator sets that demand significant data input. While effective in research contexts or bespoke modelling for policy advice, their complexity and data requirements limit their usability in cases where data availability, technical expertise, or resources are constrained.

In addition, most existing methodologies address energy efficiency (EE) and renewable energy (RE) separately, with only a few enabling their joint assessment within a common framework (EPA 2018). This separation limits the ability of policymakers, practitioners, and other stakeholders to consistently compare different climate neutrality options or to support impact assessments of decarbonisation scenarios. A common framework is particularly important given the increasing recognition of the synergies and potential trade-offs between energy efficiency and renewable energy deployment.

To address these limitations, a methodological framework for the assessment of various climate neutrality options was developed within the SEED MICAT project[1]. The framework aims to enable the assessment of multiple impacts at various governance levels, including the EU, national, and local/regional levels. It supports a wide range of use cases, such as the evaluation of policy measures and programmes, the analysis of customised scenarios, or the assessment of specific energy efficiency actions and renewable energy technologies.

The framework allows for both ex-ante and ex-post evaluations, thus supporting analysis throughout the policy cycle from planning and implementation to completion. It provides a simplified yet flexible structure to quantify and monetise social, economic, and environmental impacts of different climate neutrality strategies and compare them with a view to specific impacts or overall using different cost-benefit indicators. Given the need for broad applicability, the framework is based on impact factors or functional relationships developed for the individual impact indicators (see Table 1) for an overview of impact indicators quantified in SEED MICAT[2]). These are directly linked to input parameters from technologies, or measures under evaluation, i.e. energy savings in the case of energy efficiency improvement actions or installed capacity for renewables.

Table 1: Overview of Social, Economic and Environmental impact indicators quantified in SEED MICAT.

Social impacts	Economic impacts	Environmental impacts
Alleviation of energy poverty	Impact on energy system costs	Energy (cost) savings
Reduction in excess cold weather mortality	Impact on energy intensity	Greenhouse gas savings (savings of direct carbon emissions)
Avoided asthma cases due to reduced exposure to indoor dampness	Impact on public budget	
	Impact on GDP	Impacts on RES targets

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[1] https://micatool.eu/seed-micat-project-en/

[2] An overview of indicators can be found on the SEED MICAT project website including factsheets for each indicator, with equations provided as part of the tool documentation

Social impacts	Economic impacts	Environmental impacts
Air pollution-related health impacts - ***Air pollution-related mortality*** - ***Air pollution-related morbidity*** - ***Working days lost***	Impact on employment	Reduction in air pollution emissions
	Impact on asset value of buildings	Impact on critical raw material resource use
	Import dependence	Land-use changes

The methodology is designed to be user-friendly, requiring only a minimal set of mandatory inputs, along with the specification of the time frame and geographic scope. Mandatory data to be entered by tool users are **energy savings** for energy efficiency improvement measures and **installed capacity** for renewable energy supply options. Users can enhance the accuracy of results by entering additional, optional data instead of relying on default values included in the tool. These are either global parameters applying to all measures or measure-specific parameters that can be adjusted. This flexibility allows the tool to be applied in diverse settings, including data-scarce environments or by laypersons.

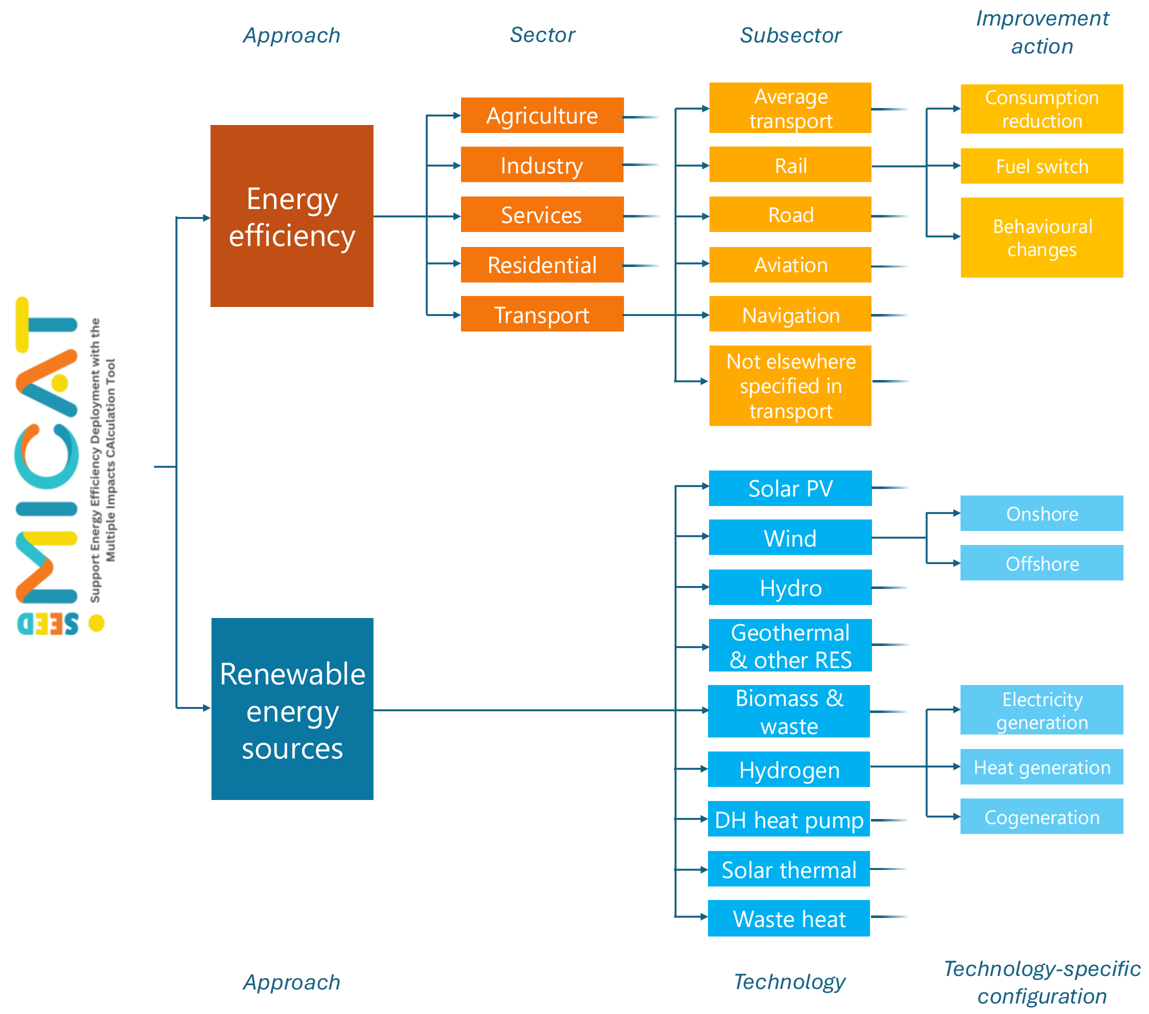
2 Method details

2.1 Inputs and calculations to enable indicator quantification

2.1.1 Disaggregation of energy efficiency and renewable energy measures

In order to account for the different impacts of energy efficiency and renewable energy solutions, they need to be grouped into categories that reflect their impact on indicators. Furthermore, solutions within a category should have similar default values across the methodology's parameters, to enable the use of a single default value. As a result, the MICATool disaggregates measures according to Figure 2.

Figure 2: **Overview of disaggregation for energy efficiency and renewable energy measures**



Upper level of disaggregation

On the one hand, this is done by distinguishing between sectors energy efficiency, as they boast very different default values and effects on indicators. The considered sectors encompass the main sectors **agriculture, industry, services, residential, and transport**. These are further differentiated on the level of subsectors: where applicable (industry and transport), more specific data are provided, for the other sectors (agriculture, services, and residential) the values of the sectors are used. Thus, since all sectors and subsectors are covered on the subsectoral level, this is the most frequently used level of disaggregation in indicator calculations.

For renewable energies, there is no comparable level to the sectors, while the different renewable technologies have an equivalent role as the subsectors for energy efficiency. The covered energy efficiency technologies are shown in Table 2.

Table 2: Overview of available EE subsectors (subsectors of industry and transport merely indicated) and RE technologies.

EE-ID	Energy efficiency subsectors	RES-ID	Renewable energy technologies
1	Average agriculture	1	Solar photovoltaics (PV)
2	Average industry	2	Wind
2.1	*Iron & steel*	3	Hydro
2…	…	4	Geothermal & other RE (e.g., tidal)
3	Average tertiary	5	Biomass & waste
4	Average residential	6	Hydrogen power plant
5	Average transport	7	Heat pump for district heating
5.1	*Rail*	8	Solar thermal for district heating
5…	…	9	Waste heat for district heating

Lower level of disaggregation

Yet, even within a sector or RE technology, measures and installations can have very different impacts, requiring a further categorisation to reflect this systematically. While end-uses fulfil the required criteria to some extent, they do not distinguish sufficiently the effects of different measures relating to the same end-use. For example, the impact of thermal insulation and behavioural measures in residential space heating have completely different effects on indoor climate and linked indicators. This is also the case for renewables, with configurations strongly influencing typical values (e.g. the electricity generation patterns, costs, and capacity factors of run-of-river starkly differs from lakes & dam hydropower).

As a result, the methodology uses energy efficiency improvement actions, as done inter alia by Thema et al. (2019) in the COMBI project[3]. Improvement actions group similar measures within a sector, for instance thermal insulation in the residential sector, which inter alia includes facade and roof retrofitting, thermal insulation, and window replacement. A similar approach was taken by introducing configurations for renewables, specifying the scale, type, or output of the selected technology. An overview of specified improvement actions and configurations, albeit partly adjusted in name and description to the sector, is shown in Table 3.

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[3] While the website of the COMBI project is not available anymore, reports and deliverables are available in the SEED MICAT library.

Table 3: Overview of energy efficiency improvement actions and Renewable configurations as well as mapping to the relevant sectors and technologies from Table 2.

Energy efficiency Improvement Action	Relevant EE-IDs	Renewable configurations	Relevant RES-IDs
Building envelope insulation	3, 4	Rooftop	1
Fuel switch	1, 2, 3, 4, 5	Utility-scale	1
Energy efficiency improvements of heating systems	3, 4	Onshore	2
Electric appliances	3, 4	Offshore	2
Cooking and water heating	3, 4	Lakes & dams	3
Organisational or behavioural changes	3, 4, 5	Run-of-river	3
Energy-efficient electric cross-cutting technologies	1, 2	Electricity	4, 5, 6
Process-specific savings	1, 2, 3	District heat	4, 5, 6, 7, 8, 9
Consumption reduction of vehicles	5	Cogeneration	4, 5, 6

2.1.2 Determination of mandatory input

Only a few variables are suitable as central mandatory inputs, as they must meet several criteria: they should scale well with most indicators, be commonly available when describing a measure, and be pragmatically and reliably convertible to other scaling variables when a direct link to indicators is lacking.

These criteria reduce the suitable variables to three, reflecting different approaches:

1) number of single measures implemented
2) energy quantity, (i.e. energy savings and renewably produced energy)
3) total costs of the measures.

The first approach defines measures based on the count of specific actions implemented, such as the number of insulated roofs, replaced heating systems, or installed photovoltaics or windmills. This method relies on tangible, discrete units that are typically reported in the context of project implementation or policy evaluation. However, to link each individual measure to the variables used for scaling multiple impact indicators, each one would need to be converted into an appropriate proxy value—an approach that would require building and maintaining a very extensive and complex database.

Secondly, energy quantity could be used as input, since the majority of multiple impacts scale quite well with energy savings and renewably produced energy. However, certain impacts, such as added value or employment rather scale with investments. Moreover, especially in early policy planning stages, these figures tend to be scarce, particularly pertaining to expected energy savings.

Finally, investment costs are often known or estimated when designing or describing a decarbonisation policy measure. Yet, merely a few indicators scale with this input, which would lead to an error propagation to the vast majority of indicators due to the necessary conversion.

To conclude, each variable has shortcomings with a view to the methodological requirements. Nevertheless, with these different aspects in mind, energy quantity has been specified as mandatory input for the methodological framework and the subsequent indicators. The main reason is the reliable relationship to most indicators, with merely a few needing adjustments.

For renewables, installed capacity, by contrast, is widely available across all levels of policy and project documentation. It is commonly used in national renewable energy targets, energy plans, scenario studies, RE support schemes, and investment plans. It provides a consistent and easily retrievable metric that can be converted into estimates of energy generation with reasonable accuracy, based on standard or context-specific capacity factors for each RE technology. Thus, this conversion enables a reliable calculation of indicator values in impact categories, where installed capacity or energy quantity is the relevant scaling variable. Moreover, capacity data are generally disaggregated by technology type, allowing for differentiated assessments across the various renewable energy technologies evaluated in the MICATool.

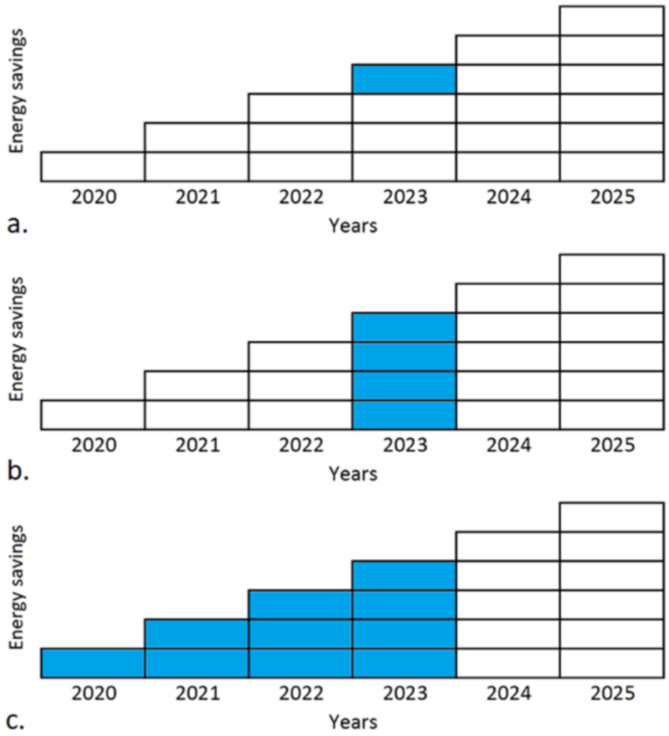
When energy quantity is used as the primary input, it is essential to clarify which type of energy quantity is being considered. Energy savings (and similarly, renewable energy generation) can be measured in three main ways: new annual savings, total annual savings, and cumulative savings:

- New annual savings refer to the reductions achieved through measures implemented within a specific year (Figure 3a).
- Total annual savings capture all reductions realised in a given year, including those resulting from measures introduced in previous years (Figure 3b).
- Cumulative savings encompass the total reductions accumulated across all years since the first measures were applied (Figure 3c).

In all cases, both savings and renewable energy generation are only counted for a duration corresponding to the lifetime of the respective measure (Schlomann et al. 2015).

In the MICATool, total annual energy savings and total annually generated energy are used (Figure 3b) as inputs, given that most scenarios and measure assessments provide energy savings in this form. In addition, since most impacts accrue over the whole lifetime of the measure, these are proportional to total annual savings. For the remaining indicators with one-time impacts from implemented measures (e.g. employment effects, impact on gross domestic product), new an-nual savings are calculated from the difference of total annual savings of a given year and the sum of new annual savings of all prior years that are still within the lifetime of the measure. The same approach is applied analogously for renewables.

Figure 3: The three approaches to accounting energy savings: new annual savings (a.), total annual savings (b.), and cumulative savings (c.) (based on Schlomann et al. (2015)).



2.1.3 Ex-post and ex-ante evaluation

The methodology allows for both ex-post and ex-ante evaluations. In order to enable this as reliably as feasible, a combination of past statistical and projection data is used as reference baseline. Statistical data are used for all available years, with future and near past values stemming from the latter.

However, many indicators used in the tool are intrinsically relative, such as air pollution, where the result is the avoided emissions and not the new total amount of emitted pollutants. Thus, the baseline is merely relevant for non-linear indicators requiring absolute values, such as energy intensity or import dependence. In these cases, the reference baseline is used to calculate the impact with and without energy savings. Yet, underlying trends from the past and the projection feeding the baseline are reflected in various parameters. Inter alia, the emission coefficients depend on the assumed energy generation mix, industrial machinery stock, modal split in transport, etc.

For **ex-post** assessment, national energy balances from Eurostat serve as the reference baseline, as they offer a highly accurate representation of the energy system and actual energy consumption across sectors and energy carriers. When assessing measures **ex-ante**, projection data of the PRIMES[4] Reference Scenario 2020 is used as reference baseline (European Commission et al. 2021).

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[4] PRIMES (Price-Induced Market Equilibrium System) is a large-scale applied energy system model that provides detailed projections of energy demand, supply, prices and investment in the future for European Union (EU) Member States. PRIMES has been extensively used by the European Commission (EC) to analyse the required energy sector transformations of EU's energy and climate policy packages Capros et al. 2019.

2.1.4 Allocation of energy savings and generated energy to energy carriers

In order to calculate primary energy savings and provide inputs for indicators, energy savings and renewably generated energy need to be allocated to savings by energy carrier (only relevant for energy efficiency) and converted to primary energy carriers. The relevant process is described in the following sections.

Energy mix of final energy savings

A key difficulty in providing input to indicators is the determination of the energy mix saved, so which energy carriers have been saved among total savings. The simplest approach is to assume all energy carriers' consumption has been reduced proportionally to their share in the sector, end-use, or the consumption linked to a certain improvement action. Given the methodology's emphasis on improvement actions within sectors, using the related energy mix would thus follow this approach. However, these data are not systematically available across sectors and countries, which poses a challenge to meeting the methodology's goal of comprehensive coverage. Instead, energy mixes are typically provided by statistical offices or the EU Reference Scenario 2020 on a (sub-)sectoral or end-use basis, not considering improvement actions. To overcome this, the methodology uses a workaround described in the following section.

Conversion to improvement action energy mix

In order to generate an assumption on the energy mix affected by a certain measure, the relationship between the energy mix of the improvement action and of the related sector is examined using consistent past data and/or scenario modelling. For every combination of sector and improvement action, this relationship is expressed mathematically by a vector providing a factor for each energy carrier:

$$\chi_{e,s,ia} = \frac{1}{n_y} \sum_y \frac{E_{e,s,ia,y}}{E_{e,s,y}} \qquad (1)$$

- $\chi_{e,s,ia}$: Sector to improvement action energy carrier coefficient (for a given final energy carrier e, sector s, and improvement action ia).
- $E_{e,s,ia,y}$: Energy consumption of final energy carrier e relevant to improvement action ia within sector s in year y.
- $E_{e,s,y}$: Energy consumption of final energy carrier e in sector s in year y.
- n_y: Number of observed years.

To calculate the energy mix on improvement action level, this vector is multiplied elementwise with the sector's energy mix vector. After normalizing the vector, the improvement action energy mix is obtained, resulting in the following savings for each energy carrier:

$$\Delta E_{e,s,ia,y} = \lambda_{e,s,ia,y} \cdot \Delta E_{s,ia,y} = \frac{\chi_{e,s,ia} \cdot \lambda_{e,s,y}}{\sum_e \chi_{e,s,ia} \cdot \lambda_{e,s,y}} \cdot \Delta E_{s,ia,y} \qquad (2)$$

- $\Delta E_{e,s,ia,y}$: Savings in energy carrier e through improvement action ia in sector s in year y.
- $\Delta E_{s,ia,y}$: Savings through improvement action ia in sector s in year y.
- $\lambda_{e,s,ia,y}$: Share of energy carrier e in consumption related to improvement action ia within sector s in year y.
- $\lambda_{e,s,y}$: Share of energy carrier e in consumption in sector s in year y.

This approach has the advantage of utilising widely available sectoral energy mix data. Since the coefficient vector is relatively stable over time, only the sectoral data need periodic updating. Additionally, this allows users to adjust the data to suit their specific needs by modifying the sectoral data, which is much easier to gather at EU, national, regional, or local levels.

Fuel switch

In case of improvement actions relating to fuel switches, the approach to define the corresponding energy mix is more complex. Since impacts such as air pollution are affected by the complete emissions of the removed as well as the installed technology, the total energy demand needs to be calculated, using the input energy savings, the typical efficiency of the main combustion technologies linked to energy carriers before and after a fuel switch, and user-input shares of removed and newly installed energy carriers:

$$E_{s,ia,y} = \Delta E_{s,ia,y} \cdot \frac{\sum_e(\eta_{\mathrm{ANTE},e,y} \cdot \lambda_{\mathrm{ANTE},e,s,ia,y})}{\sum_e(\eta_{\mathrm{POST},e,y} \cdot \lambda_{\mathrm{POST},e,s,ia,y}) - \sum_e(\eta_{\mathrm{ANTE},e,y} \cdot \lambda_{\mathrm{ANTE},e,s,ia,y})} \qquad (3)$$

- $E_{s,ia,y}$: Total energy consumption of installed technologies related to the fuel switch improvement action *ia* within sector *s* in year *y*.
- $\eta_{\mathrm{ANTE/POST},e,y}$: Typical efficiency of technologies linked to energy carrier *e* in year *y* before (*ante*) and after (*post*) a fuel switch.
- $\lambda_{\mathrm{ANTE/POST},e,s,ia,y}$: User input share of energy carrier *e* before (*ante*) and after (*post*) the fuel switch improvement action *ia* within sector *s* in year *y*.

In a second step, the effect of the fuel switch is allocated to the different energy carriers. This can also result in negative savings for some energy carriers (tantamount to increases in consumption) or savings larger than total savings (when compensated by negative savings of other energy carriers). The savings (whether positive or negative) for each energy carrier can be calculated using the following equation:

$$\Delta E_{e,s,ia,y} = \lambda_{\mathrm{ANTE},e,s,ia,y} \cdot \left(E_{s,ia,y} + \Delta E_{s,ia,y}\right) - \lambda_{\mathrm{POST},e,s,ia,y} \cdot E_{s,ia,y} \qquad (4)$$

Limitations

The default assumptions based on fallback values are naturally subject to inaccuracies, due in part to regional differences from national averages and the likelihood that the sector-to-improvement action coefficient changes over time. As a result, inaccuracies might occur when relying on the default values, which still allow to generate approximate results with little data.

However, thanks to the option to adjust the affected energy carrier shares (as well as the energy carrier shares of removed and newly installed technologies), the results' accuracy can be significantly increased by the user.

Primary energy savings

This indicator converts final energy savings and renewably generated energy into primary energy savings, a result which is also used in several other indicators. For this approach, there are two different processes:

- Energy carriers that are not produced through transformation processes (i.e., oil, coal, gas, biomass and waste) are directly attributed to the respective primary energy carriers,
- Energy carriers generated in transformation processes (i.e. electricity, heat, hydrogen and synthetic fuels (amalgamated in the methodology as H2)) are allocated to primary energy carriers, using relevant energy mixes or substitution mixes and conversion efficiency coefficients.

Allocation of H2, electricity, and heat savings as well as avoided heat generation

he conversion of final energy carriers H2, heat, and electricity includes two steps: the allocation to primary energy carriers (and electricity), from which they are generated and calculating the necessary inputs to generate the energy considering plants' efficiency. The process is implemented as a cascade through the three relevant final energy carriers and starts with the allocation and conversion of hydrogen, then heat, and finally electricity. This is due to the fact that both hydrogen and heat might be generated from electricity, which then has to be converted into its sources.

Thus, the final energy savings attributed to one of these three energy carriers are first multiplied with the relevant generation mix, which describes the share of each primary energy carrier (and electricity) in the generation of the respective final energy carrier. Then, to account for conversion losses, each resulting value has to be divided by the related conversion efficiency from primary energy carrier (or electricity) to the respective final energy carrier to find out primary energy savings while also accounting for transformation losses:

$$\Delta E_{pe,y} \;= \Delta E_{e,y} \cdot \lambda_{pe,e,y} \,/\, \eta_{pe,e,y} \qquad (5)$$

- $\Delta E_{pe,y}$: Savings in primary energy carrier pe in year y.
- $\Delta E_{e,y}$: Savings in final energy carrier e (either H2, heat, or electricity) in year y.
- $\lambda_{pe,e,y}$: Share of primary energy carrier pe in generation of final energy carrier e (either H2, heat, or electricity) in year y.
- $\eta_{pe,e,y}$: Efficiency of the conversion process from primary energy carrier pe to final energy carrier e in year y.

For energy efficiency measures as well as renewably generated heat, $\lambda_{pe,e,y}$ describes the typical contemporary national share of different primary energy carriers in H2, heat, and electricity generation. However, for renewably produced electricity, substitution factors are used to better reflect energy market effects. Effectively, according to the merit-order principle energy markets adhere to, some energy carriers are more likely to be saved when less electricity is used. This is reflected in these substitution factors, specifying how much electricity from other power plants is typically avoided by an average energy unit produced by a certain renewable energy technology. The substitution coefficients were derived by comparing the electricity generation for two PRIMES policy scenarios: a baseline case and a variant with higher renewable energy penetration in the energy system. These coefficients indicate how much electricity generated from conventional fossil-fuel sources is displaced by renewable production, taking into account each EU country's energy mix, its projected evolution over time, and current and planned energy policies.

Differentiation between the substitution rates of individual renewable technologies, was then assessed based on their estimated capacity factors. Renewable technologies with low-capacity factors (e.g., solar PV) were assumed to replace more peaking fossil-fuel power plants (e.g., oil/gas), compared to those with higher capacity factors (e.g., run-of-river hydro) which align more closely with baseload plants (e.g., nuclear). Combining these assumptions with the overall substitution coefficients, calculated in the first step, results in the amount of electricity from conventional power plants which is avoided by one unit of electricity generated from a given renewable technology.

This differentiated approach is supported by academic and policy literature. Several studies emphasise the importance of using marginal emissions factors and time-specific generation data to accurately estimate displacement effects. For example, Hawkes (2010) and Brinkman et al. (2021) demonstrate how marginal generation rather than average generation determines the actual emissions avoided by renewable technologies. This is especially relevant in the case of intermittent, variable and non-dispatchable technologies like solar and wind, where primary energy savings and emission reductions vary depending on which conventional generation is displaced in that specific point in time (Baker et al. 2013; van Kooten 2016).

Within the MICATool, each renewable technology's annual electricity or heat output is linked to a corresponding set of fuel-specific substitution coefficients. This ensures that the resulting multiple impacts, including avoided greenhouse gas emissions or reductions in air pollutants, are estimated in a consistent and realistic manner. Moreover, the method allows for the substitution pattern to evolve over time in response to changes in the energy mix and decarbonisation pathways in the European Union and its Member States. In summary, the approach captures the diversity of RE technologies and their interaction with the broader energy system, thereby enabling a robust and differentiated assessment of multiple impacts across technology types.

Given the available data from the EU Reference Scenario 2020 for ex-ante evaluations, the inputs to cogeneration power plants are solely allocated to electricity generation. Thus, the input to cogeneration plants is not accounted for in the generation of heat, resulting in heat being accounted as a "free" add-on to the generated electricity. This approach has been chosen, since the ex-ante data available for cogeneration plants do not allow a more detailed allocation of primary energy inputs to electricity and heat generation or even to dedicated electricity and cogeneration power plants. As a consequence, heat from cogeneration is not accounted for in the conversion of final to primary energy consumption. Thus, unless default values are altered, heat savings only affect dedicated heat generation, not cogeneration. This also makes sense, since cogeneration is generally more efficient than dedicated heat generation, so that savings in heat demand should primarily affect the latter.

Limitations

The main shortcoming of the primary energy savings energy mix is the oblivion towards energy market effects in the case of electricity savings through energy efficiency. Therefore, a merit-order-based analysis would result in different energy carriers being saved in the short term than just their general share in electricity and heat generation. However, because this simplified methodology lacks time resolution, it cannot accurately reflect the merit order, as the input data do not support reliable assumptions about when during the day energy savings occur. At the same time, the typically low temporal resolution of energy efficiency scenarios makes it unclear whether this issue can be effectively addressed.

Similarly, a long-term reduction of energy consumption or lowering of energy consumption increases would result in certain power generators being decommissioned or not constructed in the first place. However, in the course of the energy transition, decommissioning and new construction of power generation capacity have become political decisions rather than market-driven results. Thus, it is difficult to predict the effects for all EU Member States. Therefore, in order to provide consistent figures, energy shares in generation are used to predict saved energy carriers, stemming from the combined reference baseline. Moreover, the methodology still allows to adjust the assumed underlying energy mix of savings in electricity and heat generation.

2.1.5 Main parameters

The tool allows for an adjustment of parameters pertaining to a single measure. These measure-specific parameters include the energy carriers affected by a measure (see section Energy mix of final energy savings), as well as investments, lifetime, subsidy rate, and several additional parameters for residential measures.

Furthermore, some parameters also affect all examined measures. These global parameters inter alia include energy prices (described below) but also cover monetisation factors and energy mixes for country-specific electricity-, heat-, and H2-generation as well as for all subsectors.

Investments

This parameter specifies the total triggered investments linked to the input energy savings or renewably generated energy. Compared to energy quantity, investments are stated as cumulated values (Figure 3c), since this is the most frequent way these figures are issued. For certain calculations, these are then allocated to single years through linear interpolation between stated years.

For energy efficiency, total triggered investments correspond to the total capital expense (CAPEX) costs of the measures, rather than merely the subsidised or remaining costs (operative expenses (OPEX) are neglected, as most energy efficiency measures entail comparable OPEX to status quo ante). The calculation of triggered investments is done through coefficients reflecting typical triggered investments per saved energy unit from PRIMES for different improvement actions. Average energy savings for energy efficiency measures were derived by comparing the final energy consumption over time between PRIMES policy scenarios accompanying the European Green Deal policy package[5] and a counterfactual case, called the “frozen policy” scenario. The “frozen policy” scenario is a theoretical scenario which assumes that policies and instruments included in the EU legislative framework do not show any effects in the future and the technical characteristics of energy equipment, building stock, etc. remain unchanged relative to a base historical year (i.e. 2020). Similarly, the level of future investments required to achieve the energy savings realised in the policy scenarios is compared to the counterfactual case, where no additional investments are made relative to the base year.

In the case of renewable energy, total triggered investments include both CAPEX and OPEX. Default investment costs (CAPEX and OPEX) for renewable electricity generation in the MICATool are derived from the technology assumptions of the EU Reference Scenario 2020. These assumptions are detailed, accounting for factors such as wind resource quality and hub height for onshore wind, and water depth, distance to shore, and wind resource quality for offshore wind.

While such detailed parameters can significantly influence costs, with differences of up to 30% for onshore wind and over 60% for offshore wind, it is often unrealistic to expect tool users to provide all of these inputs. Therefore, the MICATool uses EU-wide average CAPEX and OPEX values from the PRIMES model as defaults for both onshore and offshore wind. Users can adjust these values in the tool by specifying CAPEX and OPEX (fixed and variable) for their specific context.

For photovoltaics (PV), PRIMES differentiates between residential, commercial, industrial, and utility-scale PV, as well as between low and very high resource areas. Assuming that users can at least distinguish between rooftop PV and utility-scale PV, the MICATool applies PRIMES-based averages for these two categories as default values. CAPEX and OPEX for other renewable electricity and heat technologies considered in the MICATool (e.g., hydropower, biomass) are likewise based on PRIMES data.

Remaining gaps are filled using the *Danish Energy Agency (DEA) Technology Data Catalogue for Electricity and District Heating* (DEA, 2025). This source provides more granular technology categories than those used in the MICATool. EU-average default values for CAPEX and OPEX (fixed and variable) are therefore calculated from relevant DEA technology entries. Values are provided for the years 2020, 2030, and 2050.

Limitations

Of course, even when disaggregated to improvement actions, such coefficients cannot cover the diversity of specific costs accruing for measures within these categories, particularly due to a lack of up-to-date large-scale studies covering different costs and configurations. As a result, relying on this conversion approach engenders an error propagation through the affected indicators, such as added value, impact on employment, energy intensity, or energy poverty.

Thus, it is recommended to replace default investments with case-specific triggered investments to improve the results’ accuracy, in case data are available.

Lifetimes of measures

The lifetime of an energy efficiency improvement (EEI) or installed RE technology defines the duration over which the implemented measure delivers savings or generates energy. This period begins

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[5] https://energy.ec.europa.eu/data-and-analysis/energy-modelling/policy-scenarios-delivering-european-green-deal_en

with the action's implementation and ends when the measure ceases to function or becomes obsolete. Lifetime assumptions are a critical input for the quantification of energy savings and generated energy and play an essential role in cost-benefit analyses (CBA), where both costs and benefits are discounted to reflect their present value. If the assumed lifetime exceeds the actual one, the estimated cost-effectiveness of a measure is overstated. Conversely, underestimating the lifetime results in undervaluing its benefits. In CBA that consider multiple impacts, it is commonly assumed that such impacts persist over the full lifetime of the action. Thus, establishing realistic lifetime values is crucial for producing robust and comparable results.

A methodology for estimating average lifetimes of EEI actions was introduced by the European Committee for Standardization (CEN) in 2007. This work provided harmonised lifetime values for several common EEI actions, including default values in cases where no EU-wide consensus could be reached (CEN 2007). The savings period, as defined, covers the full operational span of an EEI action, from its activation to the point it ceases to deliver performance.

Further guidance was issued by the European Commission in 2019 in the Recommendation on the transposition of energy savings obligations under the Energy Efficiency Directive (EED). This document, particularly Appendix VIII, presents indicative lifetime values for a wide range of energy efficiency measures across key sectors such as buildings, transport, industry and services (European Commission 2019). These indicative values build upon the CEN work but reflect updated technologies and partly provide more detailed distinctions between similar measures. For example, the European Commission (2019) list differentiates lifetimes for air-to-air, air-to-water, and geothermal heat pumps, while CEN (2007) reported a single average value for all heat pumps. Similarly, more recent technologies such as LED lighting have replaced older ones like compact fluorescent lamps.

In the context of the MICATool, multiple technologies are grouped into EEI actions. As a result, the framework applies plausible default lifetime values that represent averages across the technologies included in each action category. These values are derived from the sources provided by CEN (2007) and European Commission (2019) and are used as default assumptions within the MICATool. Users of the tool have the option to modify these lifetimes to reflect specific conditions or national data where applicable. The complete list of EEI actions used in the MICATool, along with the corresponding default lifetime assumptions, is provided in Table 4.

Table 4: Default lifetimes for EEI actions in the MICATool

EEI actions defined for the MICATool	
EEI action	**Default lifetime [years]**
Average agriculture	
Cross-cutting technologies	8
Fuel switch in existing processes	8
Process-specific savings (incl. waste-heat recovery)	8
Building envelope as well as space heating and cooling measures	8
Average industry and individual sectors (i.e. chemical & petrochemical, construction, iron & steel, machinery, mining & quarrying, navigation, non-ferrous metals, non-metallic minerals, paper, pulp & printing, textile & leather, transport equipment, wood & wood products)	
Energy-efficient electric cross-cutting technologies	8
Fuel switch in existing processes	8
Process-specific savings (incl. waste-heat recovery)	8
Building envelope as well as space heating and cooling measures	8
Average residential	
Building envelope insulation (windows, insulation, etc.)	25
Heating fuel switch including to district heating	17
Energy efficiency improvements of heating (boiler upgrade or replacement, pipe insulation, better heaters, etc.)	17
Electric appliances (wet & cold appliances, lighting, consumer electronics, air conditioning, etc.)	12
Cooking and water heating	15

EEI actions defined for the MICATool	
EEI action	Default lifetime [years]
Behavioural changes (i.e. thermostat adjustments)	2
Average tertiary	
Building envelope insulation (windows, insulation, etc.)	25
Heating fuel switch including to district heating	20
Energy efficiency improvements of heating (boiler upgrade or replacement, pipe insulation, better heaters, etc.)	17
Electric appliances (wet & cold appliances, lighting, consumer electronics, air conditioning, etc.)	12
Cooking and water heating	15
Organisational or behavioural changes (i.e. thermostat adjustments or energy management systems such as ISO 50001)	2
Process-specific savings (incl. waste-heat recovery)	8
Average transport and road	
Consumption reduction of vehicles (low-resistance tyres, sideboards on trucks, fuel additives, etc.)	9
Behavioural or driving changes (either autonomous or through regulations such as speed limits)	2
Fuel switch in vehicles (within the same mode of transport)	9
Aviation and rail	
Consumption reduction of vehicles (low-resistance tyres, side-boards on trucks, fuel additives, etc.)	20
Behavioural or driving changes (either autonomous or through regulations such as speed limits)	2
Fuel switch in vehicles (within the same mode of transport)	20

The assumed operational lifetime of a RE technology defines the period during which it contributes to electricity or heat generation. Accurate lifetime assumptions are critical in CBAs where both costs (CAPEX, OPEX) and multiple impacts are discounted to present value.

For consistency and comparability, the MICATool adopts lifetime assumptions derived from EU-level research. The following Table 5 summarises the lifetimes used for each RE technology. These values are primarily based on De Vita et al. (2018), Badouard et al. (2020) and DEA (2025), which derive lifetimes from expert input and empirical data. Sensitivity analysis on lifetime (± 5 years) is recommended to assess the robustness of results.

Table 5: Default lifetimes for RE technologies in the MICATool

RE technologies defined for the MICATool	
RE technology	Default lifetime [years]
Solar PV: rooftop	25
Solar PV: utility-scale	25
Wind onshore	25
Wind offshore	25
Hydro: lakes & dams	60
Hydro: run of river	50
Geothermal heat, other renewables (e.g., tidal)	35
Biomass & waste	25
Heat pump (ambient heat)	20
Hydrogen power plant	30
Solar thermal (utility scale)	25
Waste heat	25

Subsidy rates

The subsidy rate defines the share of the investment for measures that is not borne by the investor. Accordingly, when applied to the action-specific investment data, it provides an adjusted value to be used in the household level cost-benefit assessment. In consideration of differing financial resources across Member States and governance levels as well as technology specific cost-effectiveness gaps, by default a subsidy rate of 0 is set in the tool.

Limitations

Subsidies are frequently used in energy policy to incentivise the implementation of energy efficiency and renewable energies. These may be uniformly provided or tiered depending on the type or ambition level of a technology or the financial situation of applicants. Accordingly, applying a uniform subsidy rate across different technologies grouped within a programme and across income classes will introduce a certain inaccuracy with a view to the resulting financial burden or relief and resulting impacts, inter alia energy poverty alleviation.

2.1.6 Residential parameters

The methodological approach employed to assess certain impacts relevant for residential measures, such as energy poverty alleviation and health impacts linked to improved indoor climate requires more detailed information (inter alia, which share of the savings accrue among energy poor households, the number of affected dwellings/households, average rents and potential resulting increases, etc.). Analogously, certain additional parameters are necessary to calculate similar impacts for PV installations (as only relevant residential renewable technology).

Number of affected households

This parameter defines the number of households benefitting from the energy (cost) savings of an action that improves the energy efficiency of a dwelling (e.g., electrical appliances replacement or behavioural changes) or a residential building in total (e.g., building envelope insulation, energy efficient heating) or (partly) decarbonises the power supply (i.e. rooftop PV installation). If not specified otherwise by the user, the total energy savings or capacity input is translated to the number of affected dwellings by dividing it by a coefficient reflecting average energy savings or energy generation resulting from a single measure of the different improvement actions (data calculated from PRIMES) or PV installation. In the case of actions focused on the whole building, the result is multiplied with the average number of dwellings per building in a country.

Limitations

Relying on the application of averages in terms of specific savings and typical PV installation sizes as well as the number of dwellings per building to determine the number of affected dwellings may introduce a bias in each calculation step as it a) neglects the influence of factors such as building types, climate zones or user behaviour on the effectiveness of actions and b) fails to capture significant regional and urban–rural differences in housing structures. This can lead to over- or underestimation of the real scope of impact, especially in diverse housing markets. Furthermore, the underlying assumption is that building-focused actions are equally distributed across different residential building types (i.e., single, two and multi-family buildings) which is unlikely considering the socio-economic and procedural barriers in multi-family buildings with scattered ownership.

While using the average size of rooftop photovoltaic systems per country to disaggregate user inputs on deployed capacity represents a pragmatic solution in light of limited data availability, it introduces several limitations. National, and even more so EU averages may not accurately reflect the distribution of system sizes across different residential building types or ownership structures, particularly in the context of energy poor households. This can lead to either an overestimation or underestimation of actual installed capacity per building and, consequently, of the generated power and related energy cost savings at the household level.

Policy target factor

The policy target factor defines the share of measures and corresponding savings or generated energy that have been or are planned to be implemented in dwellings or buildings occupied by energy poor households. By default, this parameter uses the average value of four energy poverty indicators in 2019, based on EU-SILC data, in line with Article 8(3) of the EU Energy Efficiency Directive (European Union 2023), which requires Member States to achieve a proportional share of their cumulative energy savings among people affected by energy poverty, vulnerable customers, people in low-income households and, where applicable, people living in social housing. It can be adjusted to reflect specific policy targets.

Limitations

In current political practice, the setting of sub-targets to implement a share of promoted EEI or PV installations in energy poor households is not common, not the least due to a lack of a clear energy poverty definition and adequate administrative structures in many Member States. Accordingly, apart from specifically targeted funding programmes, applying the default or an adjusted factor will likely reflect a hypothetical best-case scenario rather than an accurate depiction of the real policy impact.

Renovation rent premium

The renovation rent premium defines the share of the investment for an EEI or PV installation in a rental building that is passed on to tenants via an increase of their rent. Accordingly, it functions as an adjustment factor applied to the residents' resulting energy cost savings. It is calculated by multiplying a percentage factor with the average rent of energy poor tenants derived from the 2020 Household Budget Survey (HBS) expenditure data. The default percentage factor is set at 4% based on a study by Mudgal et al. (2013) reviewing the level of energy efficiency premiums across a range of EU countries. Both elements (i.e., the average rent as well as the percentage factors) may be adjusted by the user.

Limitations

While the renovation rent premium offers a practical means to estimate the cost burden shifted to tenants following energy efficiency upgrades or PV installation, the approach has several limitations. First, applying a uniform percentage factor across countries or regions does not reflect the wide variation in legal frameworks, landlord practices, and market dynamics affecting rent increases. Second, relying on average rent figures may obscure disparities among energy poor households, especially in areas with high rent heterogeneity. Lastly, the approach assumes that rent increases directly correspond to investment costs and are uniformly applied, which may not be the case in reality due to regulatory restrictions or differing negotiation powers between landlords and tenants.

Number of households per building

The number of households per building is used to further disaggregate the energy cost savings from building focused EEI to the household level. As a default value, country specific averages are used that have been derived from the HOTMAPS database by dividing the number of occupied dwellings by the number of buildings in a country (Hotmaps Project 2018).

Limitations

The use of an average value obscures regional variances with a view to the characteristics of the building stock in which EEI are implemented. In cases, where the impact of building focused EEI in urban settings with higher building density is calculated, applying the default value will overestimate the energy cost savings per household. Accordingly, particularly for use cases on a subnational level, an adjustment of the parameter by the user is warranted.

Share of self-consumption

This parameter defines the share of the generated power on-site by rooftop photovoltaics that is directly utilised by the households in a building with the complementary value reflecting the proportion that is fed into the grid. As these complementary uses are valued at different prices, the respective distribution affects the eventual level of household energy cost savings. Since the applied approach to estimate the available generated renewable power per household assumes an equal distribution among all households in a building, for consistency reasons, the default self-consumption values need to reflect the cumulated consumption of the respectively applied number of households. While the self-consumption rate increases with the number of consuming households, in light of similar load profiles that often do not align with peak generation times and low market penetration of shared battery energy storage systems (BESS) the increase is likely not linear. The default rate across all EU Member States is set based on the results of pertinent studies on self-consumption in multifamily buildings.

Limitations

A key limitation of this approach lies in the simplifying assumptions it applies to the estimation of self-consumption rates. By assuming an equal distribution of generated electricity across all households in a building, the method overlooks differences in household size, occupancy patterns, and appliance use that can lead to substantial variation in actual consumption shares. Moreover, while the approach adjusts the default rate upwards for multiple households, it may not fully capture the diminishing marginal gains in self-consumption that occur when load profiles remain similar, and generation peaks are poorly matched to demand. The absence of explicit modelling of temporal consumption–generation mismatches, as well as the low but regionally variable penetration of shared BESS, introduces uncertainty into the calculated rates. Additionally, due to a lack of comprehensive data the default values rely on a small set of empirical studies, which may not adequately reflect differences in building typologies, climatic conditions, or national regulatory frameworks, limiting their generalisability across diverse EU contexts.

Remuneration of electricity fed into the grid

In order to monetise the share of generated electricity by rooftop PV that is fed into the grid, this parameter specifies the price per kWh the owner receives. At the national level, this value is determined by the existence and configuration of a Feed-in Tariff (FiT) or a direct marketing mechanism. While in practice the logic of price setting (i.e., fixed guaranteed remuneration over a specified period vs. market-based prices reflecting supply and demand) and the resulting price levels differ, these mechanisms are combined in this parameter for simplicity. Given the significant variation in FiT levels depending on system size, technology, and installation date, setting a single, time-fixed national price would introduce bias into the calculation of monetary returns (PV Magazine 2025). Moreover, with many countries gradually shifting from FiT schemes toward market-based remuneration models, using the average energy prices that reflect marginal production costs on commodity markets provides a more robust and forward-compatible default value.

Limitations

A limitation of this approach is that it oversimplifies the complexity and variability of remuneration mechanisms for surplus PV electricity fed into the grid. By condensing both fixed FiT schemes and dynamic, market-based pricing into a single parameter, important differences in price stability, predictability, and exposure to market volatility are not reflected, all of which can significantly influence household revenues. Using market-based commodity prices as a proxy may be particularly inaccurate for households currently under fixed-rate FiT agreements, while also failing to reflect regulatory adjustments, seasonal demand fluctuations, and regional grid constraints. This generalisation therefore reduces accuracy, especially when applied across diverse policy frameworks and market conditions in the EU.

Energy prices

These parameters specify the end-user costs of different energy carriers, with values being provided from PRIMES based on the data from the EU Reference Scenario 2020. The costs are differentiated by countries and sectors, taking future changes in energy systems into account. These values are used to estimate energy cost savings resulting from energy savings.

To estimate the economic value of electricity generated by different RE technologies, e.g. for use in CBA, we apply a simplified approach based on load-weighted average wholesale electricity prices from scenario modelling. The aim is to derive a plausible annual market value for the generated electricity from each technology.

Due to not being dispatchable, solar and wind farms will generate electricity when meteorological conditions allow for the generation of electricity. For solar energy, seasonal and diurnal variability results from the earth’s axial tilt and rotation around its own axis (Widén et al. 2015). While the effects of these factors on the solar irradiance reaching the earth’s surface are predictable, they also induce a high spatial autocorrelation between the generation of individual photovoltaic power stations within a country. An additional factor influencing the electricity generation from photovoltaics is cloud cover, which also causes a correlation between electricity generation from photovoltaics power stations depending on the geographical distance between them (Widén et al. 2015). Electricity generation from wind energy shows spatial correlation as well (Widén et al. 2015). In sum, these factors lead to a high probability that hourly capacity factors of wind and solar farms within a country are correlated. The marginal costs of PV and wind electricity generation are near zero (López Prol und Schill 2021). Therefore, PV and wind farms will generate electricity when meteorological conditions allow for the generation of electricity and displace electricity from other sources. In the current market design, the electricity price equals the marginal costs of the last plant needed to equal supply and demand. Variable renewable energies with near-zero marginal costs thereby lower wholesale electricity prices (the so-called merit order effect) (López Prol und Schill 2021). However, due to the correlation between their outputs, the market value (i.e., the revenues of selling electricity in an energy only market) of variable renewables falls in increasing variable renewable energy penetration (the so-called cannibalisation effect) (López Prol und Schill 2021). Therefore, it is important to differentiate between technologies when calculating market revenues for different generation technologies. At the same time, adding electricity storage to the grid mitigates both the merit-order and cannibalisation effect (López Prol und Schill 2021). Therefore, it is important to base the assumptions for electricity prices on scenarios that consider the effects of electricity storage and other flexibility options.

The load-weighted average wholesale electricity price $\bar{x}_j$ for technology j is calculated as follows:

$$\bar{x}_j = \frac{\sum_{i=1}^{I} w_{i,j} \cdot x_i}{\sum_{i=1}^{I} w_{i,j}} \qquad (6)$$

- $w_{i,j}$: Load of technology j in hour i.
- I: Number of hours in a year.
- x_i: Marginal costs of the plant needed to equal supply and demand in hour i.

It is assumed that the wholesale electricity price in hour i equals the marginal costs of the plant needed to equal supply and demand in hour i. Assumptions for $w_{i,j}$ and x_i are taken from the Ten-Year Network Development Plan scenarios developed by ENTSO-E and ENTSOG (ENTSOG und ENTSO-E 2025). The latest data available is from the 2024 scenarios and comprises results for the years 2030, 2035, 2040 and 2050. The wholesale electricity prices for the years in-between are estimated by linear interpolation.

Market values for electricity generated from photovoltaics or wind energy for past years will be calculated based on hourly wholesale electricity prices as published by Ember Energy Research (Ember 2025). The weights used in load-weighting the electricity prices are also based on the Ten-Year Network Development Plan scenarios. Data for missing years or regions is imputed.

In the case of district heating, we assume that revenues equal the costs of district heating net of taxes.

2.2 Aggregation and Cost-Benefit Analysis

2.2.1 Impact monetisation and aggregation

To integrate diverse impacts into a CBA, all outcomes must be expressed in a single common metric, namely monetary value. This process, referred to as monetisation, enables the aggregation of impacts that are originally measured in different physical units, such as kilograms of carbon dioxide or number of hospital visits, and allows direct comparison with investment costs. The aim is to monetise as many impacts as possible in order to provide a comprehensive picture of net societal benefits.

In the MICATool, default monetisation factors are provided for each impact. These factors are based on established methodologies and public data sources. Users may adjust the default values to reflect local conditions, specific contexts, or analytical preferences. This flexibility ensures that the tool can be applied across a wide range of geographical and policy contexts while maintaining methodological transparency.

A major methodological challenge in monetisation and aggregation is the risk of double counting. Some impacts may partially overlap or be interdependent, which can lead to inflated estimates of total benefits. To maintain credibility and reliability, the MICATool CBA framework includes only those impacts for which double counting can be excluded. This conservative approach avoids the need for complex adjustments that would require estimating the precise proportion of each additional benefit.

2.2.2 Operationalisation of the Cost-Benefit Analysis

In addition to the costs and benefits, the CBA requires further crucial inputs: a discount rate, lifetimes of the technologies and energy prices. The lifetimes of both energy efficiency improvement actions and renewable energy technologies, as well as the energy prices used to value energy cost savings and renewable energy generation, are discussed in detail in earlier sections of this report.

Discount Rates

The discount rate is a critical parameter in any CBA, as it determines the present value of future costs and benefits. A positive discount rate means that a benefit received today is valued more highly than the same benefit received in the future (Sartori et al. 2014). The higher the discount rate, the lower the value assigned to future impacts, which can significantly alter the cost-effectiveness of investments in energy efficiency or renewable energies (Hermelink und de Jager 2015).

For the societal perspective adopted in the MICATool, a social discount rate is applied. This rate is typically lower than a private, market-based discount rate because it accounts for the long-term, intergenerational welfare of society, not just the short-term returns on capital. Table 6 compares the level of social discount rates suggested in different energy studies. Based on these findings, the tool provides a reasonable default social discount rate (3%), but users have the flexibility to adjust this value. This allows for sensitivity analysis, helping users understand how robust their results are to changes in this key assumption.

Table 6: Review of social discount rates in energy assessments

Source	Social discount rate
Steinbach und Staniaszek (2015): Discount rates in energy systems analysis. Diskussion Paper. Fraunhofer ISI and Buildings Performance Institute Europe (BPIE).	**1% – 7%**
Hermelink und de Jager (2015): Evaluating our future. The crucial role of discount rates in European Commission energy system modelling.	**4%**
ifeu et al. (2018): Building sector Efficiency: A crucial Component of the Energy Transition Final report on a study conducted by Institut für Energie- und Umweltforschung Heidelberg (Ifeu), Fraunhofer IEE and Consentec**.**	**1.5%**
Sartori et al. (2014): Guide to Cost-Benefit Analysis of Investment Projects. Economic appraisal tool for Cohesion Policy 2014-2020, European Commission.	**5% (Cohesion countries)** **3% (other EU Member States)**
Sartori und Marra (2022): Economic Appraisal Vademecum 2021-2027, General Principles and Sector Applications, DG REGIO, European Commission.	**Projects 2021–2027: Member States are free to establish and use their own country-specific social discount rate; 3% can be used in the absence of a national approach**
European Commission (2023): Better Regulation Toolbox – July 2023 edition	**3%**

CBA indicators

The MICATool will offer different cost-benefit indicators to evaluate energy efficiency and renewable energy interventions, each with its own advantages and potential limitations. These indicators require the specification of discount rates and lifetimes for energy efficiency and renewable energy interventions to calculate the discounted cash flows.

To accommodate both energy efficiency improvement actions (which provide energy cost savings) and renewable energy supply technologies (which provide the value of energy generation), a more general term for these benefits is needed. We will use the term "Value of Energy" ($VE_{s,ia}$) in the following formulas, which encompasses both energy cost savings for energy efficiency improvement actions and the monetary value of generated energy for renewable energy supply technologies.

Annuity

Annuity is a variant of the Net Present Value (NPV) that converts the upfront investment cost into equal annual instalments (or annuities) over the project's lifetime using a capital recovery factor (CRF). This annuitised cost is then compared to the average annual benefits. This approach is particularly useful when costs and benefits are assumed to be constant over the lifetime. The formula for annuity of improvement action ia in sector s $A_{s,ia}$ is the following:

$$A_{s,ia} = -I_{s,ia} \cdot CRF_{s,ia} + (VE_{s,ia} + MI_{s,ia} - C_{s,ia}) \qquad (7)$$

- I_a: Initial investment for improvement action ia in sector s.
- $CRF_{s,ia} = \frac{i(1+i)^{LT_{s,ia}}}{(1+i)^{LT_{s,ia}-1}}$: Capital recovery factor.
- $VE_{s,ia}$, $MI_{s,ia}$: Annual value of energy costs and aggregated multiple impacts.
- $C_{s,ia}$: Other annual costs (OPEX such as operation and maintenance (O&M) costs).
- $LT_{s,ia}$: Lifetime of the selected improvement action.

Benefit-Cost Ratio and Cost-Benefit Ratio

The benefit-cost ratio (BCR) expresses the ratio of total annuitised benefits to total annuitised costs. A BCR greater than 1.0 indicates that benefits exceed costs, signifying a cost-effective investment. The formula for the benefit-cost ratio of action a $BCR_{s,ia}$ is:

$$BCR_{s,ia} = \frac{VE_{s,ia}+MI_{s,ia}}{I_{s,ia} \cdot CRF_{s,ia}+C_{s,ia}} \qquad (8)$$

In turn, the cost-benefit ratio (CBR) is the reciprocal:

$$CBR_{s,ia} = \left(BCR_{s,ia}\right)^{-1} \qquad (9)$$

A disadvantage of the BCR is its sensitivity to how an impact is classified (as a benefit or an avoided cost), which can artificially improve the ratio (Sartori et al. 2014). This is problematic for impacts that can either be treated as benefits or as avoided costs.

Levelised Cost of Energy

The levelised cost of energy (LCOE) indicator expresses the cost-effectiveness in a unit-based metric, typically €/kWh or €/tCO$_2$ saved. The calculation of LCOE can either be based on NPV or annuities (formula below shown for annuity) and divides the investment by the annual or lifetime energy savings/generation E_a. Both calculation approaches lead to the same values in terms of €/kWh if the annual value of energy and benefits included are constant values (Hermelink und de Jager 2015). This metric is valuable for a straightforward comparison of different energy efficiency options or renewable sources, or for comparing energy efficiency measures directly against supply-side options and is a standard way to operationalise the EE1st principle. The formula is:

$$LCOE_{s,ia} = \frac{A_{s,ia}}{E_{s,ia}} \qquad (10)$$

- $A_{s,ia}$: Annuity of action ia in sector s.
- $E_{s,ia}$: Energy savings or generation of action ia in sector s.

Application to the MICATool

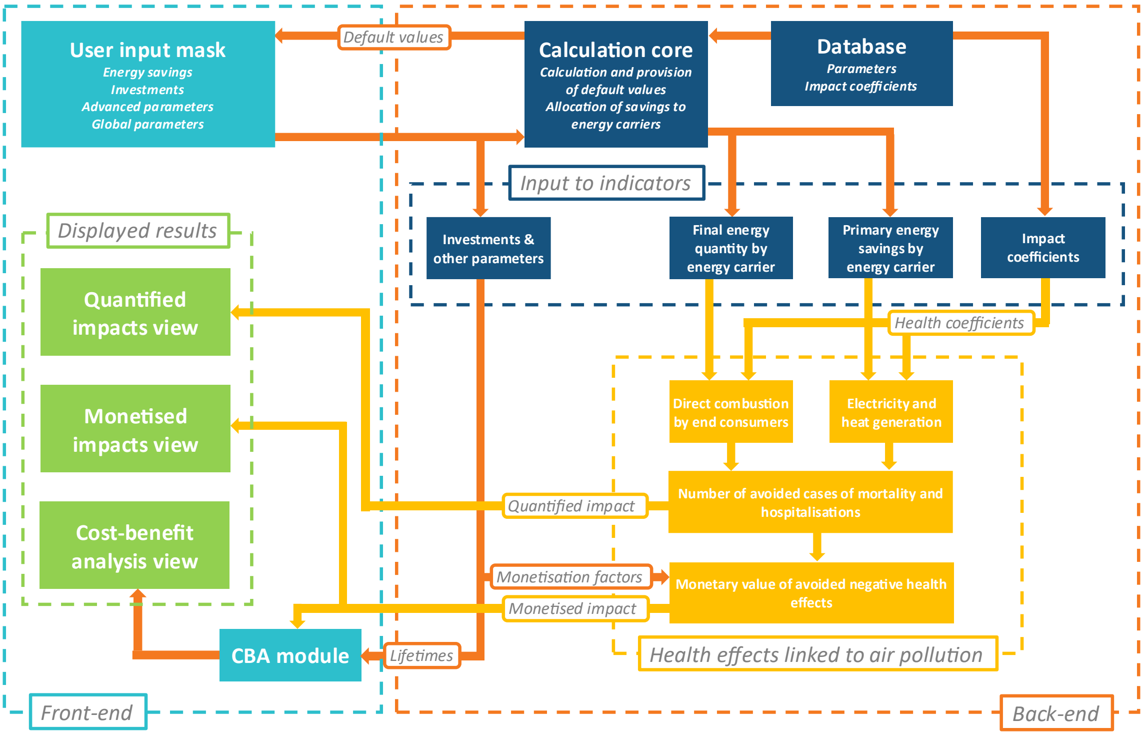
The energy quantity and investments coming from the inputs are in the form of total annual energy and cumulated investments, respectively. Therefore, for each provided year of an assessed measure (more specifically the tranche of years since the last provided year), these values are translated into new energy quantity (either savings or generation) and new investments, to enable the use of the aforementioned CBA indicators. Then, a weighted average of all these tranches is calculated to reveal the overall result of the relevant CBA indicator.

An issue arises from the fact that most available data does not exceed the year 2050, making it impossible to assess several measures with longer lifetimes using Net Present Value (NPV), which requires all monetary flows occurring during the action's lifetime to be considered. Thus, the CBA instead relies on annuity, even though the underlying assumption that costs and revenues stay constant over time must not necessarily hold true.

2.3 Integration of indicators

This framework allows for the integration of a smorgasbord of indicators. These can be integrated while drawing on the user input (including investments and adjustable parameters), the energy quantity allocated to final and primary energy carriers, the impact coefficients from the database, as well as results from other indicators. The indicator's results are then displayed in the different tool views: quantified impacts, monetised impacts, and cost-benefit analysis (the latter two merely if monetisation applicable). Figure 4 shows how indicators can be integrated into the described MICATool framework with the example of health effects of energy efficiency linked to air pollution, which is described in detail in the following section.

Figure 4: Description of the MICATool structure including exemplary integration of the indicator "Health effects linked to air pollution".



2.3.1 Exemplary indicator quantification: Health effects linked to air pollution

This impact looks at the positive impacts of energy efficiency on human health, due to reduced air pollution. In order to quantify this effect, coefficients (in terms of casualties per consumed energy in a specific country, sector, or year) similar to those used for local and global pollutants are generated using the GAINS model[6], to indicate the effects of energy efficiency on premature mortality, hospital stays and lost working days.

The developed indicator approach distinguishes between air pollution linked to end consumption and electricity and heat generation, with the addition of both producing the result. For the former, the equation uses final energy savings (excluding the values for electricity and heat):

$$\zeta_{\mathrm{MORT/HOSP},y} = \sum_e \sum_s \Delta E_{e,s,y} \cdot CF_{\mathrm{MORT/HOSP},e,s,y} \tag{11}$$

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[6] Details about the Greenhouse Gas and Air Pollution Interactions & Synergies (GAINS) model can be on IIASA's website.

- $\Delta E_{e,s,y}$: Energy quantity for a given final energy carrier *e* (excluding electricity and heat), sector *s*, and year *y*.
- $\zeta_{\mathrm{MORT/HOSP},y}$: Casualties in year *y* for mortality or hospital stays, respectively.
- $CF_{\mathrm{MORT/HOSP},e,s,y}$: Health coefficient for energy savings in energy carrier *e*, sector *s*, and year *y* for mortality or hospital stays, respectively.

In turn, air pollution for electricity and heat generation uses the allocation of generation to primary energy carriers to identify the relevant power plant types, their share in electricity and heat generation, as well as associated health coefficients:

$$\zeta_{\mathrm{MORT/HOSP},y} = \sum_e \sum_s \Delta E_{pe,e,y} \cdot CF_{\mathrm{MORT/HOSP},pe,e,y} \tag{12}$$

- $\Delta E_{pe,e,y}$: Primary energy savings from electricity or heat generation *e* for a given primary energy carrier *pe* and year *y*.
- $CF_{\mathrm{MORT/HOSP},pe,e,y}$: Health coefficient for energy savings in primary energy carrier *pe*, from electricity or heat generation *e* and year *y* for mortality or hospital stays, respectively.

2.3.2 Exemplary indicator monetisation: Health effects linked to air pollution

Using the results of the quantification, the indicator can be monetised. To do this, monetisation factors for hospital stays and premature mortality (Value of Statistical Life) from the WHO CarbonH project[7] are used and multiplied with the respective quantified result:

$$M\zeta_{\mathrm{MORT/HOSP},y} = \zeta_{\mathrm{MORT/HOSP},y} \cdot MF_{\mathrm{MORT/HOSP},y} \tag{13}$$

- $\zeta_{\mathrm{MORT/HOSP},y}$: Monetary value of avoided casualties in year *y* for mortality or hospital stays, respectively.
- $MF_{\mathrm{MORT/HOSP},y}$: Health monetisation factor for mortality or hospital stays in year *y*, respectively.

The monetised result can then be used in the CBA, alongside other monetised indicators.

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[7] Meanwhile, it has been replaced by the CLIMAQ-H Tool: https://www.who.int/europe/tools-and-toolkits/climate-change-mitigation--air-quality-and-health-(climaq-h)

3 Method validation

In order to validate this method, an exemplary calculation with 1 PJ of energy savings from building envelope insulation in the Belgian tertiary sector is carried out in the following sections. Moreover, various case studies can be found on the SEED MICAT project website. No validation is carried out for the CBA, as the methodology relies on existing and tested approaches.

3.1 Energy savings allocation

First, the total savings are allocated to final energy carriers in accordance with Equations 1 & 2, with the steps and results shown in Table 7.

Table 7: Allocation of final energy savings in line with Equations 1 & 2.

Final energy carriers	Subsectoral energy mix	Improvement action factor	Improvement action energy mix	Final energy savings
Electricity	41%	15%	11%	106.6 TJ
Oil	15%	84%	23%	225.9 TJ
Coal	0%	100%	0%	0.0 TJ
Gas	41%	86%	62%	620.6 TJ
Biomass	1%	83%	2%	20.8 TJ
Heat	2%	94%	3%	26.2 TJ
H2 & e-fuels	0%	86%	0%	0.0 TJ

Then, the final energy savings from H2 (0 TJ), heat (26.2 TJ), and electricity (106.6 TJ) are allocated to primary energy carriers in proportion to typical national H2, heat, and electricity generation (Equation 5) as an input for indicators, following the steps laid out in Table 8.

Table 8: Allocation of primary energy savings in line with Equation 5 (other includes nuclear).

Primary energy carriers	H2 allocation			Heat allocation			Electricity			Total
	Factor	Conversion efficiency	Result	Factor	Conversion efficiency	Result	Factor	Conversion efficiency	Result	
Oil	0%	56%	0.0 TJ	0%	86%	0.0 TJ	0%	41%	0.4 TJ	0.4 TJ
Coal	20%	56%	0.0 TJ	0%	82%	0.0 TJ	0%	38%	0.3 TJ	0.3 TJ
Gas	75%	72%	0.0 TJ	51%	89%	15.0 TJ	32%	57%	59.5 TJ	74.5 TJ
Biomass	0%	44%	0.0 TJ	2%	82%	0.8 TJ	5%	35%	16.5 TJ	17.3 TJ
Renewables	0%	67%	0.0 TJ	47%	100%	12.2 TJ	22%	100%	23.0 TJ	35.3 TJ
Other	0%	67%	0.0 TJ	0%	100%	0.0 TJ	41%	38%	114.8 TJ	114.8 TJ
Electricity	5%	67%	0.0 TJ	0%	250%	0.0 TJ	0%	100%	0.0 TJ	0.0 TJ

3.2 Indicator quantification and monetisation

Using these intermediate results, health effects (i.e. premature mortality and hospital admissions) due to air pollution can be calculated. Equation 11 is used for emissions arising from combustion by end consumers and Equation 12 for emissions from heat and electricity generation, with coefficients and results shown in Table 9.

Table 9: Quantification of health effects linked to air pollution.

			Factors (in # cases per TJ)		Results (in # cases)	
Origin	**Energy carriers**	**Savings**	**Mortality**	**Hospital admissions**	**Mortality**	**Hospital admissions**
Final energy carriers	Electricity	106.6 TJ	0.0000	0.0000	0.00	0.00
	Oil	225.9 TJ	0.0089	0.0044	2.02	0.99
	Coal	0.0 TJ	0.1771	0.0868	0.00	0.00
	Gas	620.6 TJ	0.0003	0.0001	0.17	0.08
	Biomass	20.8 TJ	0.0375	0.0184	0.78	0.38
	Heat	26.2 TJ	0.0000	0.0000	0.00	0.00
	H2 & e-fuels	0.0 TJ	0.0000	0.0000	0.00	0.00
Primary energy carriers: Heat generation	Oil	0.0 TJ	0.0034	0.0017	0.00	0.00
	Coal	0.0 TJ	0.0432	0.0212	0.00	0.00
	Gas	15.0 TJ	0.0002	0.0001	0.00	0.00
	Biomass	0.8 TJ	0.0116	0.0057	0.01	0.00
	Renewables	12.2 TJ	0.0000	0.0000	0.00	0.00
	Other	0.0 TJ	0.0000	0.0000	0.00	0.00
	Electricity	0.0 TJ	0.0000	0.0000	0.00	0.00
Primary energy carriers: Electricity generation	Oil	0.4 TJ	0.0096	0.0047	0.00	0.00
	Coal	0.3 TJ	0.0107	0.0053	0.00	0.00
	Gas	59.5 TJ	0.0002	0.0001	0.01	0.01
	Biomass	16.5 TJ	0.0115	0.0057	0.19	0.09
	Renewables	23.0 TJ	0.0000	0.0000	0.00	0.00
	Other	114.8 TJ	0.0000	0.0000	0.00	0.00
	Electricity	0.0 TJ	0.0000	0.0000	0.00	0.00
Sum					**3.18**	**1.56**

Using the country-specific monetisation factors for Belgium in 2020 (3 821 130 € per premature death, 5 386 € per hospital admission), the costs of premature mortality and hospitalisations can be estimated at around 12 M€ and 8 k€, respectively.

4 Limitations

Given the MICATool's objective to allow swift assessments of multiple impacts, a number of limitations emerge compared to classic energy modelling. In particular, the renunciation of feedback loops leads to inaccuracies when it comes to measures and policies significantly impacting the overall energy system. Since most calculations rely on functional relationships with fixed coefficients, assuming an energy system along the lines of the EU Reference Scenario 2020, such changes are not accounted for. Thus, a major limitation is the assumptions that all input measures and policies merely have a marginal effect on the overall energy system, which is neglectable. As a result, the MICATool is not really designed to assess nationwide scenarios or even monumental measures. If a measure is large enough to affect, for instance, the overall energy mix of electricity or heat generation, this is not reflected in the tool or results.

Moreover, additional limitations come through the selection of certain parameters and proxies (these limitations have been described at mention of the associated aspect).

5 List of figures

6 List of tables

7 Bibliography

Badouard, Thierry; Moreira de Oliveira, Débora; Yearwood, Jessica; Torres, Perla; Altmann, Matthias (2020): Final Report Cost of Energy (LCOE). Energy costs, taxes and the impact of government interventions on investments. Hg. v. Directorate-General for Energy. Available online at https://trinomics.eu/wp-content/uploads/2020/11/Final-Report-Cost-of-Energy-LCOE.pdf, last checked on 02/10/2025.

Baker, Erin; Fowlie, Meredith; Lemoine, Derek; Reynolds, Stanley S. (2013): The Economics of Solar Electricity. In: Annu. Rev. Resour. Econ. 5 (1), S. 387–426. DOI: 10.1146/annurev-resource-091912-151843.

Breitschopf, Barbara; Held, Anne; Resch, Gustav (2016): A concept to assess the costs and benefits of renewable energy use and distributional effects among actors: The example of Germany. In: Energy & Environment 27 (1), S. 55–81. DOI: 10.1177/0958305X16638572.

Brinkman, Gregory; Bain, Dominique; Buster, Grant; Draxl, Caroline; Das, Paritosh; Ho, Jonathan et al. (2021): The North American Renewable Integration Study (NARIS): A U.S. Perspective.

Campbell, Nina; Ryan, Lisa; Rozite, V.; Lees, E.; Heffner, Greg (2015): Capturing the multiple benefits of energy efficiency. Hg. v. IEA. Available online at https://www.iea.org/reports/capturing-the-multiple-benefits-of-energy-efficiency, last checked on 24/05/2024.

Capros, Pantelis; Zazias, Georgios; Evangelopoulou, Stavroula; Kannavou, Maria; Fotiou, Theofano; Siskos, Pelopidas et al. (2019): Energy-system modelling of the EU strategy towards climate-neutrality. In: Energy Policy 134, S. 110960. DOI: 10.1016/j.enpol.2019.110960.

CEN (2007): Saving lifetimes of Energy Efficiency Improvement Measures in bottom-up calculations. Final CWA draft (CEN WS 27). European Committee for Standardization. Brussels. Available online at https://publications.tno.nl/publication/34628861/cY640W/e07099.pdf, last checked on 02.10.2025.

De Vita, Alessia; Kielichowska, Izabela; Mandatowa, Pavla (2018): Technology pathways in decarbonisation scenarios. Hg. v. Directorate-General for Energy. Available online at https://energy.ec.europa.eu/document/download/c5dac2fb-4682-4795-a1b1-13f8806c9ea8_en?filename=2018_06_27_technology_pathways_-_finalreportmain2.pdf, last checked on 02.10.2025.

DEA (2025): Technology Data Catalogue for Electricity and District Heating Production. Updated May 2025. Hg. v. Danish Energy Agency. Available online at https://ens.dk/en/analyses-and-statistics/technology-data-generation-electricity-and-district-heating, last checked on 02.10.2025.

Ember (2025): European Wholesale Electricity Price Data. Wholesale day-ahead electricity price data for European countries, sourced from ENTSO-e and cleaned. Hg. v. Ember Energy Research. Available online at https://ember-energy.org/data/european-wholesale-electricity-price-data/, last checked on 09.10.2025.

ENTSOG; ENTSO-E (2025): TYNDP 2024. Scenarios Report. Available online at https://2024.entsos-tyndp-scenarios.eu/, last checked on 09.10.2025.

EPA (2018): Quantifying the Multiple Benefits of Energy Efficiency and Renewable Energy. A Guide for State and Local Governments. United States Environmental Protection Agency. Available online at https://www.epa.gov/sites/default/files/2018-07/documents/epa_slb_multiple_benefits_508.pdf, last checked on 02.10.2025.

European Commission (2019): COMMISSION RECOMMENDATION (EU) 2019/1658. on transposing the energy savings obligations under the Energy Efficiency Directive. Hg. v. Directorate-General for Energy. Available online at https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32019H1658, last checked on 02.10.2025.

European Commission (2023): 'Better Regulation' Toolbox. July 2023 edition. Available online at https://commission.europa.eu/law/law-making-process/better-regulation/better-regulation-guidelines-and-toolbox_en, last checked on 02.10.2025.

European Commission; Directorate-General for Climate Action; Directorate-General for Energy; Directorate-General for Mobility and Transport; Vita, A. de; Capros, P.; Paroussos, L. (2021): EU reference scenario 2020 : energy, transport and GHG emissions. trends to 2050. Hg. v. Publications Office. Available online at https://data.europa.eu/doi/10.2833/35750, last checked on 24.05.2024.

European Union (2023): Directive (EU) 2023/1791 of the European Parliament and of the Council of 13 September 2023 on energy efficiency and amending Regulation (EU) 2023/955 (recast). Energy Efficiency Directive. In: Official Journal of the European Union. Available online at http://data.europa.eu/eli/dir/2023/1791/oj, last checked on 24.05.2024.

Hawkes, A. D. (2010): Estimating marginal CO_2 emissions rates for national electricity systems. In: Energy Policy 38 (10), S. 5977–5987. DOI: 10.1016/j.enpol.2010.05.053.

Hermelink, Andreas; de Jager, David (2015): Evaluating our future. The crucial role of discount rates in European Commission energy system modelling. Hg. v. eceee und Ecofys. Available online at https://www.eceee.org/policy-areas/discount-rates/evaluating-our-future-report/, last checked on 02.10.2025.

Hotmaps Project (2018): Hotmaps database. Available online at https://gitlab.com/hotmaps, last checked on 09.10.2025.

ifeu; Fraunhofer IEE; Consentec (2018): Building sector Efficiency: A crucial Component of the Energy Transition. Final report on a study conducted by the Institut für Energie- und Umweltforschung Heidelber (Ifeu), Fraunhofer IEE and Consentec. Hg. v. Agora Energiewende. Available online at www.agora-energiewende.org/publications/building-sector-efficiency-a-crucial-component-of-the-energy-transition, last checked on 02.10.2025.

López Prol, Javier; Schill, Wolf-Peter (2021): The Economics of Variable Renewable Energy and Electricity Storage. In: Annu. Rev. Resour. Econ. 13 (1), S. 443–467. DOI: 10.1146/annurev-resource-101620-081246.

Makešová, Michaela; Valentová, Michaela (2021): The Concept of Multiple Impacts of Renewable Energy Sources: A Critical Review. In: Energies 14 (11), S. 3183. DOI: 10.3390/en14113183.

Mudgal, Shailendra; Lyons, Lorcan; Cohen, François; Lyons, Ronan; Fedrigo-Fazio, Doreen (2013): Energy performance certificates in buildings and their impact on transaction prices and rents in selected EU countries. Final report. Hg. v. Directorate-General for Energy. Available online at https://main.wpresidence.net/wp-content/uploads/2017/01/energy.pdf, last checked on 02.10.2025.

PV Magazine (2025): Feed-in tariffs (FITs) in Europe. Available online at https://www.pv-magazine.com/features/archive/solar-incentives-and-fits/feed-in-tariffs-in-europe/, last checked on 09.10.2025.

Resch, Gustav; Welisch, Marijke; Liebmann, Lukas; Breitschopf, Barbara; Held, Anne (2016): A prospective assessment of costs and benefits of renewable energy use in the European union. In: *Energy & Environment* 27 (1), S. 10–27. DOI: 10.1177/0958305X16638228.

Reuter, Matthias; Patel, Martin K.; Eichhammer, Wolfgang; Lapillonne, Bruno; Pollier, Karine (2020): A comprehensive indicator set for measuring multiple benefits of energy efficiency. In: *Energy Policy* 139, S. 111284. DOI: 10.1016/j.enpol.2020.111284.

Ryan, Lisa; Campbell, Nina (2012): Spreading the Net: The Multiple Benefits of Energy Efficiency Improvements. Paris (IEA Energy Papers).

Sartori, Davide; Catalano, Gelsomina; Genco, Mario; Pancotti, Chiara; Sirtori, Emanuela; Vignetti, Silvia; Del Bo, Chiara (2014): Guide to Cost-Benefit Analysis of Investment Projects. Economic appraisal tool for Cohesion Policy 2014-2020. Hg. v. Directorate-General for Regional and Urban policy. Available online at https://ec.europa.eu/regional_policy/sources/studies/cba_guide.pdf, last checked on 02.10.2025.

Sartori, Davide; Marra, Massimo (2022): Economic Appraisal Vademecum 2021-2027. General Principles and Sector Applications. Hg. v. Directorate-General for Regional and Urban policy. Available online at https://data.europa.eu/doi/10.2776/182302, last checked on 02.10.2025.

Schlomann, Barbara; Rohde, Clemens; Plötz, Patrick (2015): Dimensions of energy efficiency in a political context. In: *Energy Efficiency* 8 (1), S. 97–115. DOI: 10.1007/s12053-014-9280-8.

Sovacool, Benjamin K.; Kim, Jinsoo; Yang, Minyoung (2021): The hidden costs of energy and mobility: A global meta-analysis and research synthesis of electricity and transport externalities. In: *Energy Research & Social Science* 72, S. 101885. DOI: 10.1016/j.erss.2020.101885.

Steinbach, Jan; Staniaszek, Dan (2015): Discount rates in energy system analysis. Discussion Paper. Hg. v. Buildings Performance Institute Europe (BPIE). Available online at https://www.bpie.eu/wp-content/uploads/2015/10/Discount_rates_in_energy_system-discussion_paper_2015_ISI_BPIE.pdf, last checked on 02.10.2025.

Thema, Johannes; Suerkemper, Felix; Couder, Johan; Mzavanadze, Nora; Chatterjee, Souran; Teubler, Jens et al. (2019): The Multiple Benefits of the 2030 EU Energy Efficiency Potential. In: *Energies* 12 (14), S. 2798. DOI: 10.3390/en12142798.

van Kooten, G. Cornelis (2016): The Economics of Wind Power. In: *Annu. Rev. Resour. Econ.* 8 (1), S. 181–205. DOI: 10.1146/annurev-resource-091115-022544.

Widén, Joakim; Carpman, Nicole; Castellucci, Valeria; Lingfors, David; Olauson, Jon; Remouit, Flore et al. (2015): Variability assessment and forecasting of renewables: A review for solar, wind, wave and tidal resources. In: *Renewable and Sustainable Energy Reviews* 44, S. 356–375. DOI: 10.1016/j.rser.2014.12.019.