Economic and Social Considerations for the Future of Nuclear Energy in Society

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Deliverable 2.1: Assumptions, models, and methodology for the development of nuclear energy in EU, on the next two decades

Work Package 2

Lead Beneficiary: RATEN

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Contents

Executive Summary

The ECOSENS project includes an assessment of the sustainability performance of nuclear electric power generation for the entire life cycle considering the current development of nuclear technologies. Evolutions of the energy market in the transition toward climate neutrality are also investigated in order to discuss the role of the nuclear power in the medium and long term.

The current deliverable is devoted to methodological development. Starting with mapping of the existing sustainability assessment methodologies, a comparative analysis was performed with the involvement of experts and stakeholders. Three candidate methodologies were pre-selected for the analysis: NESA-IAEA (Nuclear Energy System Assessment), KIND-IAEA (Key Indicators for Innovative Nuclear Energy Systems), and LCA/LCIA-JRC (Life Cycle Analysis/ Life Cycle Impact Assessment). With input from expert and non-specialist stakeholders the most valuable elements of the three methodologies were identified and a proposal for a new methodology was created. The proposed combination methodology approaches the three pillars of sustainability (economic development, social development, environmental protection) through Entire Life Cycle Assessment. Its ambition is to be, as much as possible, applicable for all carbon-free electricity generation technologies.

While ECOSENS project was funded under a Euratom program and applies its resources to detailing an assessment of nuclear energy share and performance, the investigation of the possible roles of nuclear in the energy market over the medium and long term requires understanding and some predictions of the evolution of all energy technologies (especially renewables). This broadened perspective furthermore allows the expression of diverse stakeholder preferences.

The deliverable is structured in four parts plus annexes: (1) assumptions in the short term (discussing the quite predictable elements influencing energy demand such as demographics, GDP, standard of living, level of electrification, etc.), (2) models (presenting the current models of predicting the energy market evolution and the associated tools), (3) methodology (presenting the analysis of current sustainability assessment methodologies and the development of a suitable methodology for the purpose of the project), (4) considerations on the short-term development of nuclear power technology applications in Europe. A large separate section (Annexes) describes the indicators and sub-indicators selected for the ECOSENS methodology. Sixty-one detailed fiches present the main data and considerations resulting from a systematic analysis of official documents, scientific reports, research papers, and databases. This significant fund of information compiled in standardized form will furnish the basis for conducting the ECOSENS quantified life cycle assessment of nuclear power.

The report is intended to support the participation of stakeholders, who may have limited knowledge on the energy sector, in carrying forth the pluralistic discussion of assessment results.

1. Introduction

The development of a methodology for the comparative assessment of different energy technologies arises from the urgent need to transition towards more environmentally friendly and socially responsible energy sources. As societies worldwide struggle with the challenges of climate change, resource depletion, and social equity, it is imperative to form a comprehensive understanding and comparison of the impacts of various energy technologies. The last few years have witnessed more and more recognition that our energy choices of today profoundly shape the future of the planet and its inhabitants. Systematic evaluation and comparison of energy technologies will contribute to informed decisions that contribute to a more sustainable, resilient, and equitable energy landscape. It is furthermore important to conduct assessment in a transparent way, with the involvement of societal stakeholders, in order to reflect the preferences of society. ECOSENS contributes to this effort by developing assessment methodology and performing a quantitative analysis. Moreover, ECOSENS explores, on a small scale, means by which specialist and non specialist stakeholders in society can be involved in the methodological development and the later interpretation of results.

Fossil fuel-based energy sources, such as coal, oil, and natural gas, are major contributors to greenhouse gas emissions and air pollution. The resulting climate change and environmental degradation have far-reaching consequences for ecosystems, biodiversity, and human health. Developing sustainable energy technologies is crucial to mitigate these impacts and limit global temperature rise. At the same time, the potential for conventional technologies' improvement should be fairly considered to understand their possible role in the future energy market.

Energy security is crucial for the stability and prosperity of a region or country. Conventional energy sources are finite and non-renewable, and their extraction often leads to environmental degradation as well as human rights violations. As these resources become scarcer, the search for alternative, sustainable energy sources to ensure long-term energy security becomes more urgent. Regional and national contexts are very diverse from the point of view of resource reserves and the potential of new reservoirs. Importantly, dependence on imported fossil fuels can make countries vulnerable to geopolitical conflicts and price fluctuations.

Many sustainable energy technologies, such as solar, wind, and hydropower, have become increasingly cost-competitive with conventional fossil fuels. Nuclear power is today a major contributor to decarbonization of the energy sector and offers strong potential for the decarbonization of heating in particular, but it suffers from the point of view of a robust public acceptance. Developing a comprehensive methodology to assess the economic feasibility and potential benefits of this range of technologies, together with a fair understanding of the risks, can support decisions to invest in these technologies.

Public awareness of environmental issues and sustainability has grown significantly in recent years. Individuals, communities, and businesses increasingly demand cleaner and more responsible energy options. A clear methodology for comparing sustainability performances can inform consumer choices and foster engagement.

Energy technologies can have differential impacts on local communities, including health effects, employment opportunities, and land use changes. A robust assessment methodology can help identify technologies that promote social equity and minimize adverse local impacts.

Governments and international bodies are setting ambitious targets for transitioning to sustainable energy sources. To effectively design and implement policies and regulations that promote the adoption of these technologies, decision-makers require accurate, comparative information on their sustainability performances.

Advances in technology are rapidly improving the efficiency, reliability, and scalability of sustainable energy technologies. A methodology that takes into account the latest innovations and research findings ensures accurate assessments that reflect the current state of these technologies.

Energy infrastructure investments have long lifecycles, often spanning decades. Making informed decisions about technology choices requires an understanding of their long-term impacts on the environment, economy, and society.

In the literature, various electricity generation technologies have been assessed from the point of view of sustainability, including inter-comparison of alternatives based on a range of methodologies [1], [2], [3].

Considering the objectives of the ECOSENS project to assess the sustainability of the whole cycle of nuclear power at European level, three candidate methodologies are discussed in order to select the most appropriate one, or to extract from each the most valuable elements to be combined in a new methodology. Both experts' and stakeholders' views, using evaluative exercises[1], were considered in selecting the final methodology.

The candidate methodologies were the following:

> **(M1) NESA-IAEA** (Nuclear Energy System Assessment) developed by the International Atomic Energy Agency (IAEA). The holistic methodology examines all components of the nuclear cycle, structured in seven areas of investigation: (A1) Economics [4], (A2) Infrastructure [5], (A3) Waste management [6], (A4) Proliferation resistance [7], (A5) Physical protection, (A6) Environment impact (Stressors [8] and Depletion of resources [9], (A7) Safety (safety of nuclear reactors [10] and safety of nuclear fuel cycle facilities [11].
>
> **(M2) KIND-IAEA** (Key Indicators for Innovative Nuclear Energy Systems) [12] developed by IAEA in the frame of INPRO-KIND with the purpose to introduce more flexibility in selection of the criteria and indicators.
>
> **(M3) LCA/LCIA-JRC** (Life Cycle Analysis/ Life Cycle Impact Assessment) [13] developed by the European Commission's Joint Research Centre (JRC) in the frame of the Taxonomy Regulation debate to assess the entire cycle of nuclear power.

The purpose of M1 is to evaluate a national or global nuclear energy system regarding its long-term sustainability according to the INPRO defined set of basic principles, user requirements and criteria; to identify the gaps in the assessment areas for existing or planned nuclear energy systems (NES) sustainability; and to recommend follow-up actions to close these gaps. **M1** was developed by INPRO (International Project on Innovative Nuclear Reactors and Fuel Cycles) starting in 2000 [14].

M2 is devoted to the comparison of the sustainability performance of different nuclear technologies or NES development scenarios.

M3 was developed in the context of establishing the EU classification of environmentally sustainable economic activities ("EU Taxonomy" for the assessment of financial investments). LCA/LCIA-JRC aims

[1] Stakeholder input was gathered through a face-to-face workshop. The agreed report [34] detailing the participatory exercises and discussion is downloadable from the ECOSENS-project.eu website.

to assess the nuclear sector considering the entire life cycle, and to compare the sustainability performances of the most relevant energy production alternatives.

Based on the assessment exercises and further development, a methodology is proposed to assess the entire life cycle for nuclear power, suitable for performing comparisons with all the energy alternatives contributing to the sustainability performances of an energy system.

The deliverable is structured in four parts plus annexes: (1) assumptions in the short term (discussing the quite predictable elements influencing energy demand such as demographics, GDP, standard of living, level of electrification, etc.), (2) models (presenting the current models of predicting the energy market evolution and the associated tools), (3) methodology (presenting the analysis of current sustainability assessment methodologies and the development of a suitable methodology for the purpose of the project), (4) considerations on the short-term development of nuclear power technology applications in Europe. A large separate section (Annexes) describes the indicators and sub-indicators selected for the ECOSENS methodology. Sixty-one detailed fiches present the main data and considerations resulting from a systematic analysis of official documents, scientific reports, research papers, and databases. This significant fund of information compiled in standardized form will furnish the basis for conducting the ECOSENS quantified life cycle assessment of nuclear power.

2. Assumptions on short-term

Societal and technological changes will affect the demand for energy and the energy market. A three-fold projection at European level is targeted by the ECOSENS project: short-term (until 2035), medium- (to midcentury), and long-term (after 2050). The current section is devoted to short-term assumptions, for which it is appropriate to present not only projections of market development, but even predictions to be followed by strategic energy policy documents. In the separate deliverable D2.2 (Analysis of impact of societal and technological changes on the future energy market) medium- and long-term developments will be approached.

The ECOSENS assumptions are generalized in nature and are grounded in present-day trends and broadly shared expectations. It is crucial to acknowledge that beyond the project, assumptions regarding energy system development until 2035 may exhibit significant variation to the extent that they are formulated by different stakeholders holding different analytic perspectives. Moreover, the actual trajectory of developments in the energy system until 2035 may deviate from the ECOSENS selected assumptions due to factors such as groundbreaking technological advancements, shifts in policy dynamics, changes in the economic landscape, and the emergence of unforeseen events including climate, geopolitical, or public health crises.

The following general assumptions that could shape the energy system were selected as relevant and reasonable:

(GA1) **Energy transition**:

- there will be a significant increase in the deployment and utilization of renewable energy sources such as solar, wind, hydro, and geothermal. Advancements in technology, declining costs, and increased awareness of environmental concerns are expected to drive this transition.

(GA2) **Energy efficiency**:

- there will be a continued emphasis on energy efficiency measures across various sectors; this includes the adoption of energy-efficient technologies, building retrofits, and improved industrial processes. Energy efficiency gains can help reduce overall energy demand and mitigate the need for additional generation capacity.

(GA3) **Decentralization and distributed generation**:

- the energy system is expected to become more decentralized, with a greater focus on distributed generation. Localized renewable energy installations, including rooftop solar panels and community wind farms, will play a more significant role in meeting energy demands. This shift may be facilitated by advances in smart grid technologies and energy storage systems.

(GA4) **Electrification of transportation**:

- there will be a significant increase in the electrification of transportation, including personal vehicles, public transportation, and freight. This shift is driven by the increasing availability of electric vehicle models, improving battery technology, government incentives, and growing environmental consciousness. As a result, the demand for electricity will rise, requiring an expansion of the power grid and charging infrastructure.

(GA5) **Energy storage:**

- the development of efficient and cost-effective energy storage technologies, such as batteries, pumped hydro, and advanced thermal storage systems, will accelerate. Energy storage is crucial for managing the intermittency of renewable energy sources and ensuring a reliable and resilient energy system.

(GA6) **Integration of smart grids and digitalization**:

- the energy system will become increasingly digitalized, incorporating advanced metering infrastructure, real-time data analytics, and smart grid technologies. This integration will enable better demand-side management, grid optimization, and more effective integration of renewable energy resources.

(GA7) **Increased focus on energy resilience**:

- with growing concerns about climate change, extreme weather events, and geopolitical uncertainties, there will be a greater emphasis on energy resilience. This includes diversification of energy sources, investments in robust grid infrastructure, and improved disaster response and recovery mechanisms.

(GA8) **Shift in energy policies**:

- governments and international bodies are expected to implement more ambitious climate policies, including carbon pricing, renewable energy targets, and stricter regulations on greenhouse gas emissions. These policies will drive the transition to cleaner energy sources and incentivize innovation in the energy sector.

Significant technological developments in the energy sector are expected at the level of whole EU, driven by the need to transition towards a sustainable, low-carbon economy. These advancements have been shaped by the EU's commitment to combat climate change, reduce greenhouse gas emissions, and achieve energy security.

The main technological developments in the energy sector, at the horizon of 2035, are:

(TA1) **Electrification of Transport**:

- by 2035, the EU has experienced a significant shift towards electric mobility. Electric vehicles (EVs), both private and public, have become widespread, supported by an extensive network of charging infrastructure. The advancement of EV technology, including improved battery range, faster charging, and more affordable prices, has accelerated the transition away from fossil fuel-powered vehicles, reducing emissions in the transportation sector.

(TA2) **Green Hydrogen Production:**

- green hydrogen has emerged as a key focus area for the EU's energy transition. Electrolysis technologies powered by renewable energy have enabled the production of hydrogen without carbon emissions. The EU has invested in scaling up green hydrogen production capacity, building hydrogen infrastructure, and fostering cross-border hydrogen networks to facilitate its use in various sectors, including industry, transportation, and energy storage

(TA3) **Energy Efficiency and Demand Response**:

- energy efficiency measures have played a crucial role in reducing energy consumption and optimizing resource utilization. Building codes and standards have been strengthened to ensure new constructions meet high energy efficiency criteria. Additionally, advanced energy management systems and demand response programs have been implemented, enabling consumers to adjust their energy usage based on real-time pricing signals, contributing to load balancing and grid stability.

(TA4) **Renewable Energy Expansion:**

- the EU has witnessed a substantial increase in renewable energy generation. Solar, wind, and hydropower have become the dominant sources of electricity, with offshore wind farms and floating solar installations playing a significant role. Technological advancements in renewable energy systems, including more efficient solar panels, advanced wind turbines, and innovative energy storage solutions, have contributed to the expansion of clean energy.

(TA5) **Grid Modernization and Smart Grids**:

- the EU has invested heavily in upgrading and modernizing its energy grid infrastructure. Smart grids have become prevalent, enabling the integration of renewable energy sources, energy storage systems, and electric vehicle charging infrastructure. These grids leverage advanced sensors, automation, and real-time data analytics to optimize energy distribution, reduce transmission losses, and enhance grid resilience.

(TA6) **Decentralized Energy Systems**:

- the EU has witnessed a rise in decentralized energy systems, such as microgrids and community energy projects. These systems empower local communities to generate, store, and distribute their own renewable energy, fostering energy independence and resilience. Prosumers (consumers who also produce energy) have become more common, with individuals and businesses generating electricity through rooftop solar panels or small-scale wind turbines.

(TA7) **Energy Storage Technologies**:

- energy storage technologies have seen remarkable progress, addressing the intermittent nature of renewable energy sources. Battery storage systems, including advanced lithium-ion batteries, flow batteries, and emerging technologies like solid-state batteries, have become more efficient and cost-effective. Moreover, large-scale pumped hydro storage, compressed air energy storage, and innovative solutions like hydrogen storage and power-to-gas have gained enough maturity, enabling the balancing of energy supply and demand.

(TA8) **Carbon Capture and Storage (CCS) and Carbon Capture and Utilization (CCU)**:

- to address emissions from industrial processes and hard-to-decarbonize sectors, the EU has made progress in deploying carbon capture technologies. Carbon capture and storage and carbon capture and utilization technologies have been further developed, allowing for the capture and storage of carbon dioxide emissions or converting them into useful products, such as synthetic fuels or chemicals.

On the other hand, energy demand, and implicitly the energy system, is influenced by the economic, social, technological developments, considered in this report as specific assumptions.

(SA1) **Demographics:**

- the EU-27 population is reported as 446.8 million in 2019 [15]. The maximum should be reached in 2026 as 453.3 million (+1.5 %). After that, a tendency of decrease is predicted, with 452.7 million in 2030. Therefore, no important changes in the total population will occur. However, looking to the demographic groups, there is a systematic tendency of ageing, but on short-term the connected changes in the demographic structure are irrelevant.

Assumption D1: Population growth	**EU- 27** from 0.447 b (2019) to 0.453 b (2030)

(SA2) **Gross Domestic Product:**

- for EU27, in the period of interest for our analysis (2020-2030) the annual rates of economic growth "will remain roughly in line with the advanced economy growth", around 2% [16], lower than the global average rate (2.5-3%).

Table 3.1 Projections for the economic annual rate growth (data from [17])

2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
2.14%	2.13%	2.12%	2.11%	2.10%	2.09%	2.08%	2.06%	2.03%	2.00%	1.97%

Assumption GDP: Economic growth	**EU27** Annual rate around 2%, approximately constant

(SA3) **Impact of energy efficiency measures on energy demand:**

- in 2018 the Energy Efficiency Directive (EED) entered into force, updating the 2012 directive (27/2012/EU). The EU energy efficiency target for 2030 of at least 32.5% (compared to projections of the expected energy use in 2030) was transposed in the national energy and climate plans (NECPs) for 2021-2030. In July 2021, the Commission adopted the integration of EED as part of the Green Deal package, which contains legislative proposals to meet the EU objective of at least 55% reduction in greenhouse gas emissions by 2030. A reduction of 36% for final energy consumption and 39% for primary energy consumption by 2030 compared to the 2007 (reference scenario) is targeted. The EU considers the energy efficiency as the first priority in the practical applications, investment decisions, and policy. The objective stated in 2018 consists of a reduction of the consumption by 32.5% in 2030. In 2021 the target was redefined adding an additional effort of 9% reduction (2030 vs 2020), in absolute terms the "overall EU energy consumption should be no more than 1023 million tonnes of oil equivalent Mtoe of primary energy and 787 Mtoe of final energy by 2030" [18]. In 2022 the Commission has increased the ambition from 9% to 13% (reduction vs 2020), in absolute terms 980 Mtoe (primary energy), respectively 750 Mtoe (final energy consumption).

Assumption EE: Impact of energy efficiency measures	**EU27** A reduction of the primary energy consumption at least with 30% (vs 2020)

(SA4) **Standard of living:**

- the natural tendency of the social development is to improve the quality of life. The urgency of the measures to prevent the climate changes or at least to mitigate their impacts introduces some constraints. In [19] an important effort was dedicated to understand if it is possible to meet the 2050 climate targets in conditions of ensuring good living standards. The team involved in the work has developed an application ("Global Calculator") that includes a model of the lifestyle (consumption patterns, daily needs, diet, travels, etc.) and its impact in the energy, materials and land requirements. According with [19] the following evolutions are plausible: (1) access to electricity will increase at 94% (2050) vs 84% (2014), (2) the winter average indoor temperature could rise to 19^{0}C (2050) compared with 16^{0}C (2014), whereas the summer average indoor will decrease to 24^{0}C (2050) compared with 27^{0}C (2014), both influencing the energy demand (heating and cooling), (3) people will own more appliances (e.g. for washing machines from 0.8 (2014) to 1.0 (2050) units per urban household), (4) increasing of the travels, from 8300 km/capita (2014) to 12400 km/capita (2050), with an increase of 400 km of travels by air, and an increase of the travels share by car from 37% (2014) to 40-45% (2050), (5) the increasing in food equivalent consumption from 2180 kcal/capita/day (2014) to 2330 (2050) with impact in the land using.

Assumption Liv: Standards of living: increasing progressively	**EU27** Relevant increase in heating & cooling, appliances in households, travels

(SA5) **Electrification:**

- the decarbonization of transport, heating, and cooling sectors, together with a high development of the appliances will increase the share of electricity in the total energy mix both at the global and EU level. An improved access to electricity is an important factor at global level, but with less importance at the EU level since the most of EU27 countries has a 100% access factor, and the others greater than 99%. In EU the most important factors in electrification are: enlarging the electric vehicles (EV) share, and electrification of heating. For 2030 the target in EVs is estimated at 35% [20]. According with the ambition of Green Deal, EU entered the Electric Decade. Currently, the EU's vehicle fleet consists of 63 million units (cars, vans, buses, trucks) [20]. It should be noted that an additional contribution will be achieved by the indirect use of electricity via hydrogen (and its derivatives) production based on electricity. The green hydrogen option will allow the greening of sectors difficult by direct electrification.

Assumption El: Impact of electrification	**EU27** A share of EVs of 35% in 2030

The specific assumptions, and their background (including the draft deliverable 2.2), were presented to two international groups of stakeholders for discussion and contextualization. While the short webinar, and the second face-to-face discussion conducted at the ECOSENS Scientific Event of August 2023, were insufficient to fully review and assess the assumptions, the assumptions were generally accepted as "reasonable". Nonetheless a diversity of observations was recorded, giving insight into stakeholder worldviews and reasoning as to the evolution of energy questions, and gathering advice on factors believed to affect assumptions.[2]

[2] The agreed report [44] is downloadable from the ECOSENS-project.eu website.

3. Models

In this section, the EU Reference Scenario [21] is discussed as basis for the understanding of the probable development of the European Union covering the next decades. The scenario is one of the European Commission's key models used for analysis in the energy and transport areas in the context of climate actions.

The scenario is developed by using a set of tools, each tool incorporating different models, addressing e.g. socio-economic development, energy demand, or impact of climate policies. A discussion of the tools and models is included in the current section. It is intended to clarify the capabilities on the models (including the understanding of limitations and uncertainties) and in that way be of use to the stakeholders involved in interpreting the assessment of the sustainability performances of energy alternatives.

Currently, the methodology to estimate EU socio-economic development, energy demand and impact of policies [22] is based on the set of models presented in Fig. 4.1 (steps of the methodology) and the tools presented in Table 4.1.

Table 4.1 Models and tools used for EU estimations

	Models	Tool
1	EU – energy system	PRIMES
2	Greenhouse gas and air pollution information and simulation	GAINS
3	Global biosphere management model	GLOBIOM
4	Common agricultural policy regional impact	CAPRI
5	General equilibrium economic model	GEM-E3
6	Contribution of the various energy types (fossil fuels, nuclear, renewables) and energy vectors, to future energy needs	POLES-JRC

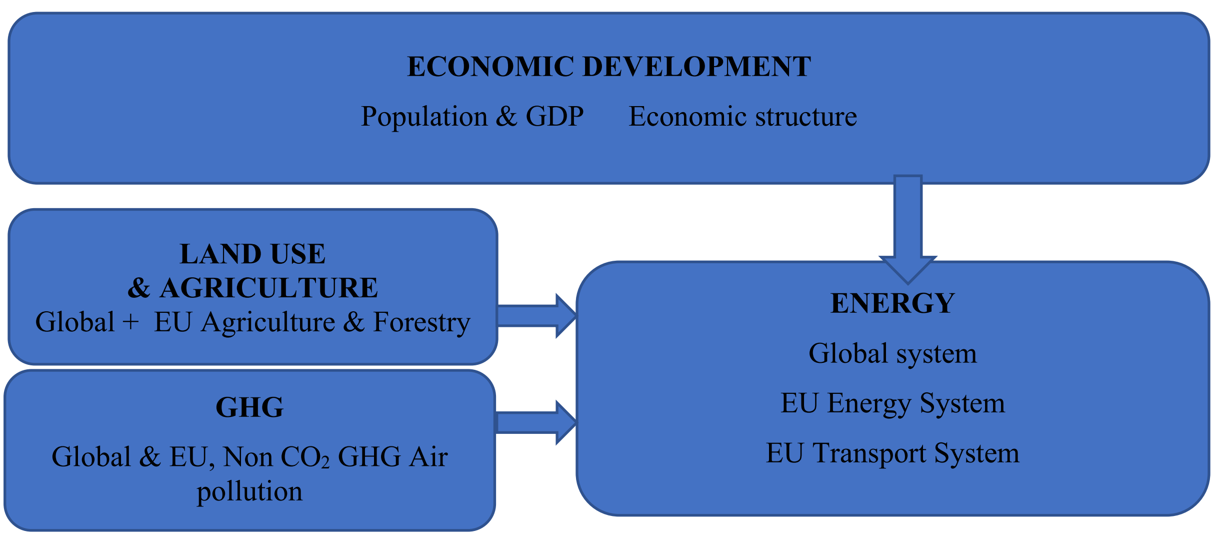


Fig. 4.1 The main steps of the EU methodology

PRIMES [22] is a tool aimed to simulate the energy consumption and the energy supply system in the EU. The basic approach is the market equilibrium in the European Union and at the level of each MS. The model simulates the volumes of energy to obtain optimal market equilibrium characterized by utility maximization, cost minimization and market balance. Mathematically, PRIMES solves an equilibrium problem with equilibrium constraints which allows prices to be explicitly determined [24]. The tool considers the carbon prices for the different components.

In terms of decision-making process, micro economic theory is used, centering the decisions of individuals and small groups (such as families, clubs, firms), and governmental agencies. This approach is combined with some engineering considerations, covering all energy sectors and markets. An explicit detailed energy demand is considered together with the energy generation system and the associated emissions. The tool includes a set of sub-modules dedicated for the simulation of: transport sector, biomass supply, industrial non-CO_2 emissions. The calibration of PRIMES was achieved by considering EUROSTAT data for 2000-2015.

According with [24] PRIMES is more adapted to simulate long-term evolutions rather than short-term. It "includes non-linear formulation of potentials by type (resources, sites, acceptability etc.) and technology learning" [24].

PRIMES includes the following models: (1) transport model (PRIMES-TREMOVE) with recent developments for synthetic fuel and hydrogen, (2) residential and service model (PRIMES BuiMo) considering multi-agent building renovation, heating and cooling, and enlarged use of equipment/appliances, (3) industry model with a high-resolution description of the sectors and processes, including the directly use of hydrogen and synthetic fuels, and the electrification impact, (4) biomass supply model, considering the biomass supply with land constraints and sustainability regulations, (5) electricity and heat/steam supply and market model, considering the pan-European market simulation over the grid constraints and technically restrictions, (6) gas supply, simulating the gas infrastructure with the interconnexion with Eurasian and Middle-East areas, (7) fuels and storage model, covering Hydrogen, Synthetic fuels, Power-to-X, CO_2 capture from the air and biogenic, CCS/CCU, (8) IEM model, simulation of the EU market: intraday, day-ahead.

GAINS (Greenhouse gas and Air Pollution Information and Simulation) [25] model simulates the air pollutants and the GHGs in an integral approach, considering their interactions. The emission sources and the dispersion in the atmosphere is estimated together with the costs of the emissions for a given economic development. The estimations are detailed on the sub-sectorial level. The impacts on the human health are estimated based on fine particulate distribution, ground-level ozone, vegetation damage by ground ozone, acidification of ecosystems and nitrogen deposited in excess in the soil. The tool is calibrated using UNFCCC emission data.

GLOBIOM-G4M (Global Biosphere Management Model) is the model used for an integrated simulation of agriculture, bioenergy and forestry sectors devoted to the analysis of the global competition for land-use. The models included details for 20 global most important crops, the livestock production activities, forestry commodities and the energy transformation pathways [26]. The approach is at globally level, for EU a decomposition in MSs is possible. Model includes a projection of emissions from land use, land use change and forestry (LULUCF).

CAPRI (Common Agricultural Policy Regional Impact) [27] is an economic partial equilibrium model, devoted to the simulation of the global agricultural sector with a focus on the EU. There are some limitations, mainly connected with the lack of the potential interactions with the non-agricultural sectors, except the land use.

GEM-E3 (General equilibrium economic model) [28] is a model simulating the whole world economy, the major regions and the EU MSs, taking into consideration the links between economy, environment and energy. The dynamic growth, the investment, labor, price formation and consumptions are represented in the GEM-E3 with regional peculiarities. At the same time, the tool includes the technology progress.

POLES-JRC (Prospective Outlook on Long-term Energy Systems) [29] estimates the contributions of the various energy types (fossil fuels, nuclear, renewables) and energy vectors, to future energy needs. It is a world energy-economy partial equilibrium simulation model. It may be used at global, regional, country- (all G20, OECD, and main non-OECD economies), sectoral-level to study the impact of energy and climate.

These instruments were used to simulate the energy demand, the energy mix, and the impact on the emissions for various scenarios. An **EU Reference Scenarios 2020 (RS)** was developed [30] in order to have a common basis for the understanding of possible evolutions.

This scenario is the starting point in the possible evolution of the EU and may help stakeholders to understand the possible roles of the energy alternatives on short- medium- and long-term. The policy framework in place in 2020 was considered to build the scenario. It should be noted the scenario was built taking into considerations the results of the consultation process involving national experts and stakeholders from MSs. The aim of RS is to reveal the possible evolution considering, as starting point, the current policies, therefore not compulsory to reach climate neutrality. From this perspective the results of simulation of RS can provide the analytical basis for new policy proposals.

The key elements of RS are presented below:

(1) a progressive decoupling of GDP growth from energy demand growth is projected (with almost implemented in 2030); in Fig.3.2 the projection of the decoupling is presented, with normalization to 100 (for 1995).

(2) a decreasing of GHG emissions is predicted for most of the sectors, and particularly in electricity generation, despite the increase in the demand, based on the rising of the ETS prices and increasing the maturity of renewables. For short- to medium-term a reduction by 43.8% (2030 vs 1990) is predicted.

(3) non-CO2 emissions will decrease substantially in waste and HFC (Hydrofluorocarbon), and at a small extent in agriculture

(4) energy demand will decrease (see Fig. 4.2) progressively based on the energy efficiency, technology developments, recycling and industry shifting, but the electricity demand will increase substantially due to the decarbonization objectives involving great effort for electrification of heating & cooling (H&C) and transport.

(5) from the point of view of the contribution of different sectors, the consumption of the industry will decrease gradually (Fig. 4.3) mainly due to energy efficiency measure and technological development leading to a gradual reduction of the energy intensity.

(6) the share of electricity in total final demand will reaches 26% (2030) and 33% (2050) (compared to only 22% in 2015); the increase will be determined by: (i) electrification of H&C buildings (heat pumps and more appliances), (ii) electrification of transport (EVs), including indirectly by hydrogen and synthetic fuel, (iii) shifting to electricity industrial processes.

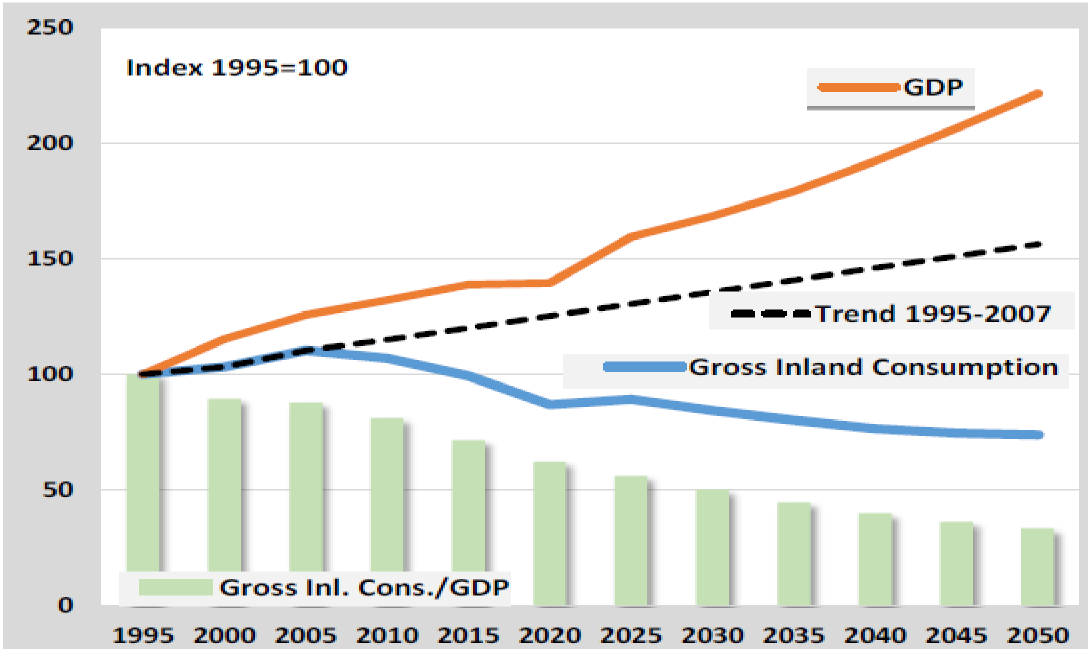


Fig. 4.2 Projection of RS for the decoupling between GDP and GIC (source [30])

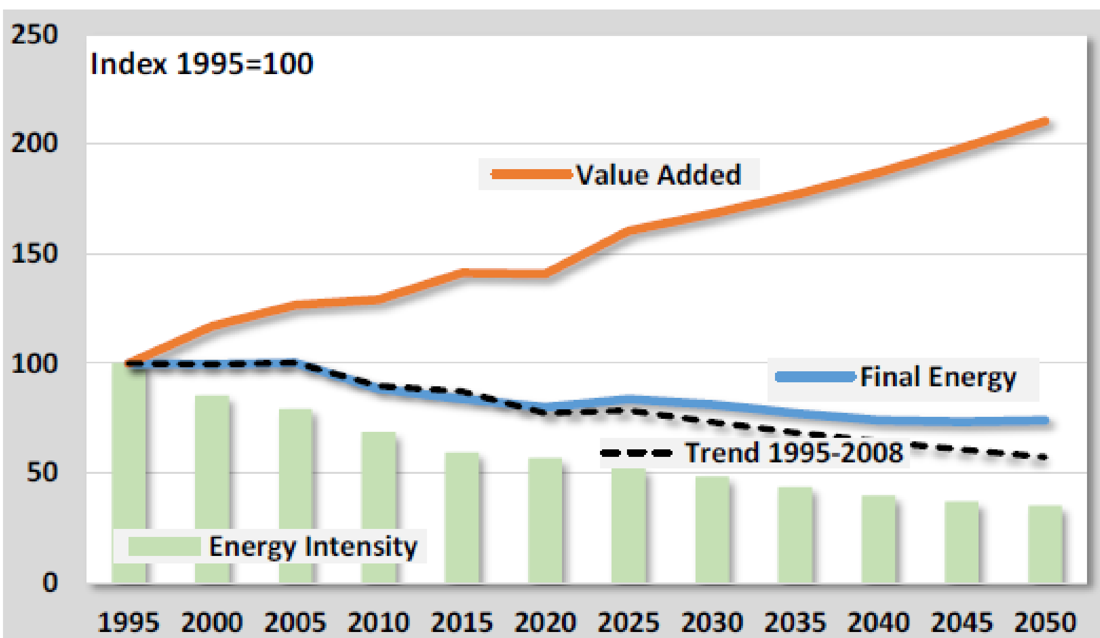


Fig. 4.3 The evolution of the energy intensity in industrial sector (source [30])

(7) structural changes in industry are projected "to shift towards high value-added and less energy-intensive products" and "growing electrification and fuel switching". The most important envisaged sectors are iron & steel, non-ferrous metallurgy, chemistry, pulp and paper. Based on these changes, the net import of fossil fuel will decrease in 2050 to "almost a third of the projected peak in 2025". The oil will remain at the main form of energy import.

(8) energy efficiency will contribute to a substantial decrease of the energy consumption (including the and transport sector) by 2030 with 29.6% (vs 2007) for the primary energy, and a target of 32.5% for the final energy consumption (not reached in RS)

(9) the overall renewables share will reach 33.2% (2030 total energy mix).

(10) the energy mix will rely on renewable (RES) energy (and nuclear production for some MSs), whereas a major drop in lignite and coal use will occur, together with a major limitation of the gas (and oil) use due to the depletion of domestic production. Reference scenario (RS) projected 59% (2030) of electricity generation from RES, and 75% (2050). The main contribution of RES will be from intermittent sources (wind and solar), with an estimation for 2030 of 42% (from total RES). Solar will expand from 87.8 GW (2015) to 307 GW (2030) and 513 GW (2050). The RS projected 18% of electricity generation in 2050 for solar PV. In Fig.4.4 the projected evolution for the energy mix is presented.

(11) the largest increase in the electricity mix will be of the wind energy generation (30% of total net electricity in 2030, triple in comparison with 2015). The installed capacity is estimated at 349 GW (2030), respectively 508 GW (2050), compared with 127 GW (2015). The offshore capacity will increase very fast at 95 GW (2050) from 5.9 GW (2015).

(12) natural gas continues to play a role acting as bridge fuel, based on low carbon intensity relative to oil & solids, and based on their flexibility characteristics in complementarity with intermittent RES generation. RS considers only a modest decrease of gas share until 2030 and low increase in 2050. However, the current geopolitics changed a lot the conditions for gas, the new policy being oriented to more energy independence (drastically reduction of gas import from Russia). RS projected an investment in new capacities of gas with a total installed power of 290 GW.

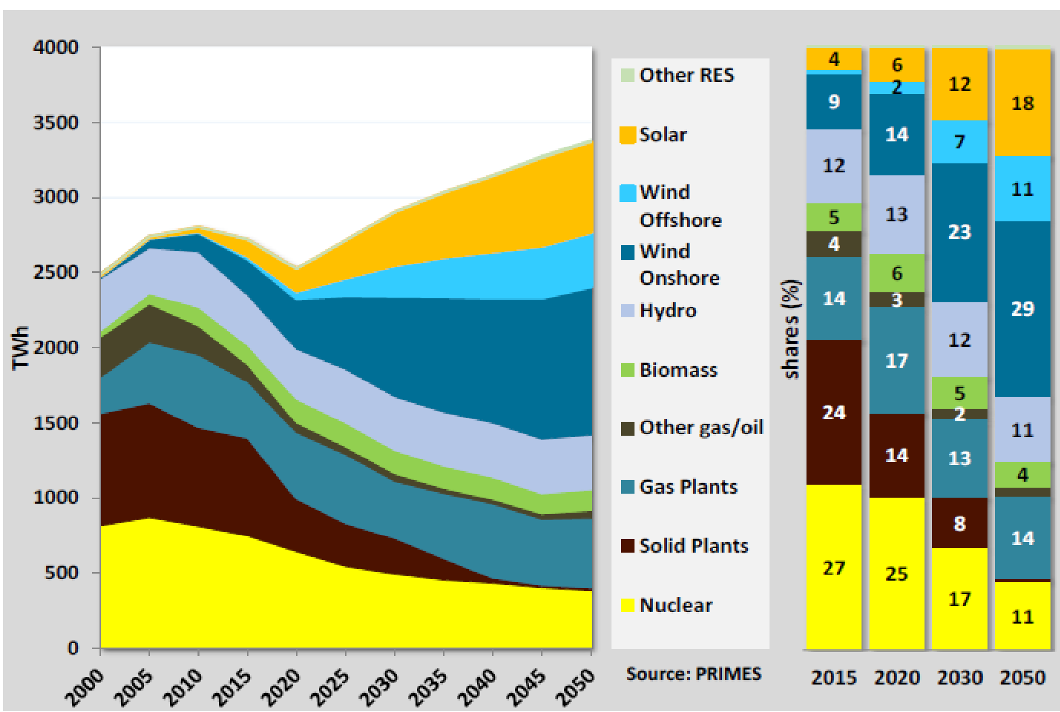


Fig. 4.4 Projection of RS for the electricity by plant type (source [30])

(13) for nuclear power the RS projected a progressive decline from 107 GW (2020) to 94 GW (2030) and 55 GW (2050) based on decision to phase out in some MSs, and delays in the new buildings. The main factor for nuclear capacity is represented by lifetime extensions. A possible boosting of the investment by SMR deployment is not considered in the RS.

(14) storage will be crucial for the balancing of the system, especially for the MS's system with large penetration of variable RES, generating high requests for flexibility services in the power system. Currently, the gas plants and grid interconnectivity are the main source of balance between generation and demand. Some countries have hydro capacities, and may develop hydro pumping as a feasible and effective storage capacity. In the RS an acceleration of the storage is foreseen after 2030 by pumped storage, batteries, power-to-X, including hydrogen production. The evolution of projected storage capacity is presented in Fig. 4.5.

(15) in the transport sector a significant increase of the share of EVs is projected in conjunction with the growing green electricity production and a stimulating policy on CO2 emission cuts and support for recharging infrastructure

(14) in the buildings sector, large efforts will be devoted to renovation of the insulation (envelope) and replacing H&C by energy efficient devices (particularly high-efficiency heat pumps); a significant contribution to EU's 2030 energy efficiency final energy consumption target is expected

(15) transport activity will increase both for passenger and freight, but with a faster growing for freight. The projected evolution is presented in Fig. 4.6. Considering the evolutions in the transport technologies including the energy efficiency the projected consumption by transport is presented in Fig.4.7

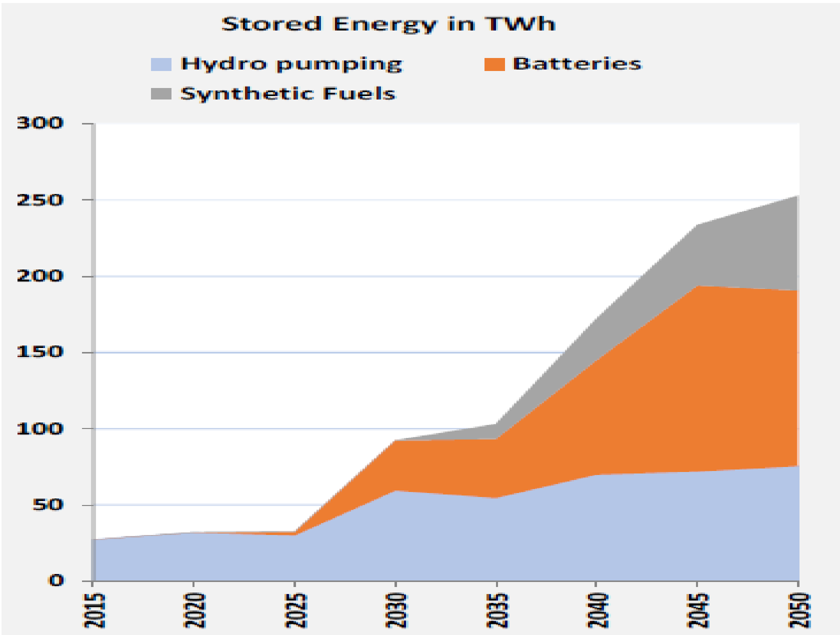
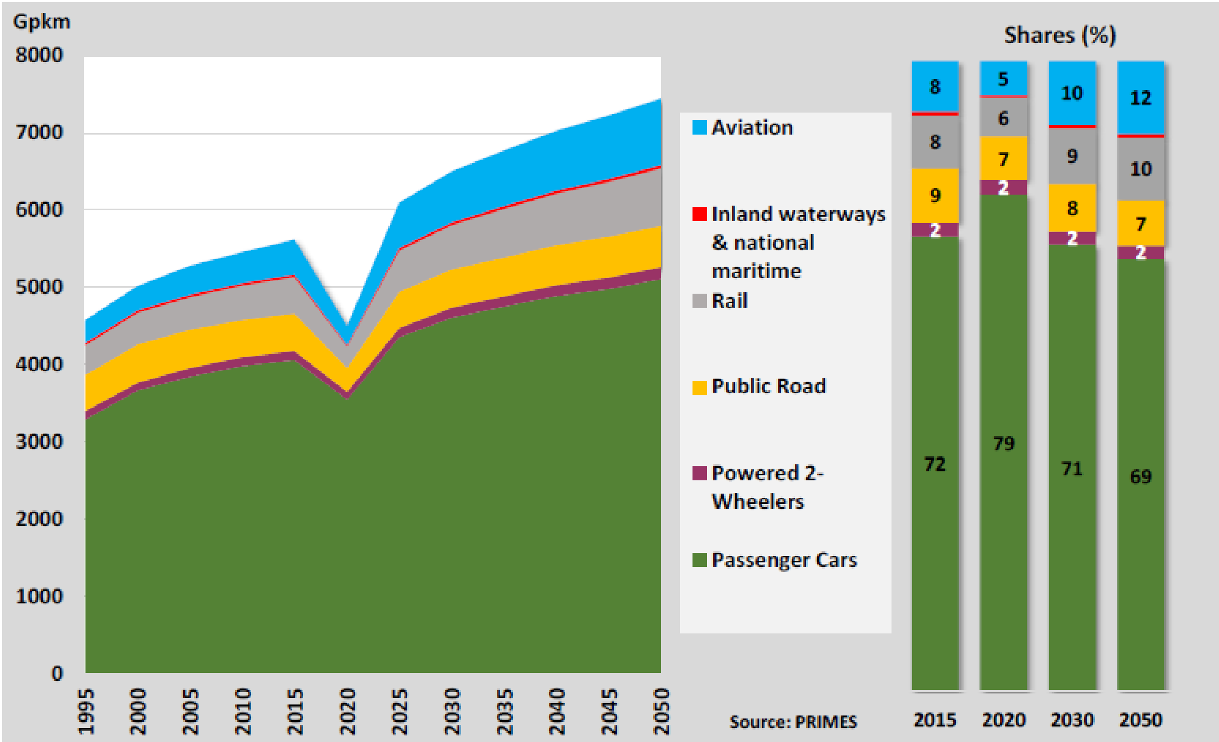


Fig. 4.5 Projection of RS for the storage capacity (source [30])



Note: Aviation includes only intra-EU aviation

Fig. 4.6 Projection of RS for transport sector (source [30])

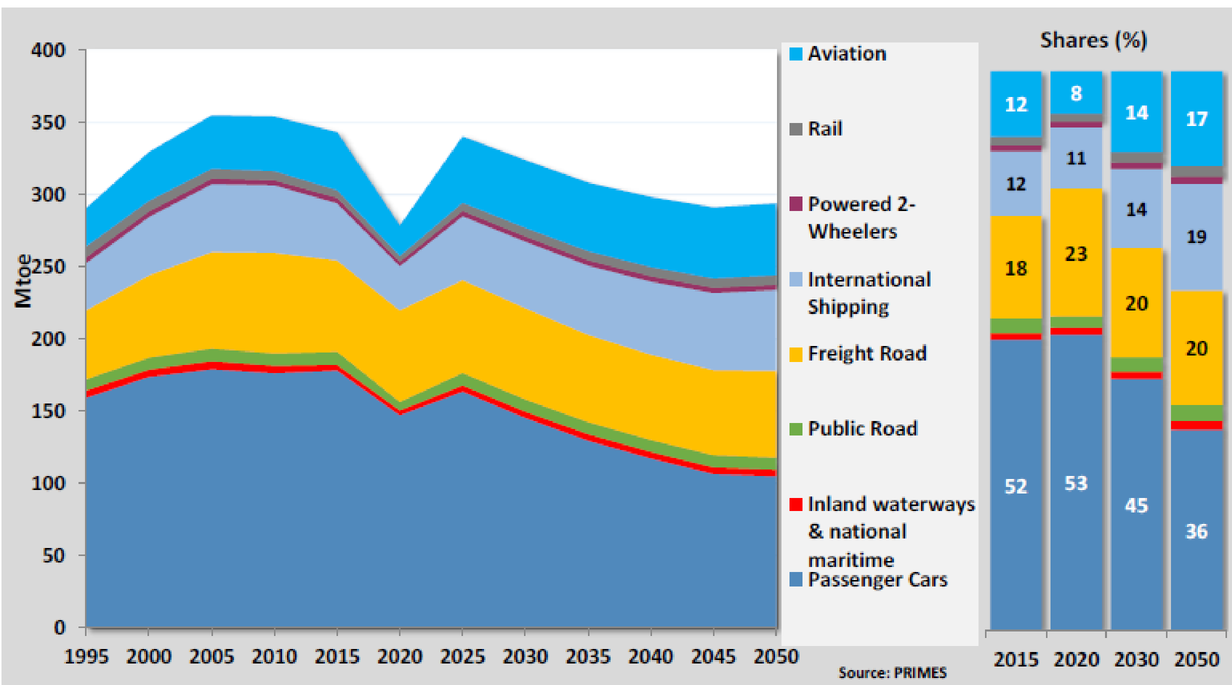


Fig. 4.7 Projection of RS for energy consumed in the transport sector (source [30])

4. Methodology

.1 4.1 Short description of the methodologies

This section is devoted to the inter-comparison of some methodologies used in the recent years for the sustainability assessment of nuclear energy. Sustainability assessments generally address three pillars: (1) economic development, (2) social development, and (3) environmental protection.

Over time various methods and methodologies were developed in order to assess the sustainability performances of the various electricity generation technologies including their inter-comparison. Some of them are oriented to measuring the environmental impacts across the entire life cycle of an energy technology, such as to evaluate resource use, emissions, and energy consumption from production to disposal. Other methods are focused on the Environmental Impact Assessment (EIA) estimating the environmental consequences of energy projects or technologies and discussing elements like air and water quality, biodiversity, and ecosystem health. Other methodologies are structured as Carbon Footprint Analysis (quantifying greenhouse gas emissions associated with energy production and usage), or Social Impact Assessment (SIA) by evaluating the social effects of energy projects on communities and stakeholders (considering aspects like health, equity, and social well-being). Beyond of the these, a large variety of methods are developed and used in different contexts. A set of them are based on MCDA (Multi-Criteria Decision Analysis) integrating multiple sustainability criteria to rank and select energy technologies and considering economic, environmental, and social aspects for decision-making.

Considering the objectives of the ECOSENS project to assess the sustainability of the whole cycle of nuclear power at European level, three candidate methodologies are discussed in order to select the most appropriate one or to extract from each the most valuable elements to be combined in the proposed assessment exercise.

These candidate methodologies are the following:

> **(M1)** MCDA methodology **NESA-IAEA** (Nuclear Energy System Assessment) devoted to a holistic analysis of all components of the nuclear cycle, structured in seven areas: (A1) Economics, (A2) Infrastructure, (A3) Waste management, (A4) Proliferation resistance, (A5) Physical protection, (A6) Environment impact, (A7) Safety
>
> **(M2)** MCDA methodology **KIND-IAEA** (Key Indicators for Innovative Nuclear Energy Systems) developed to compare the sustainability performances of the innovative nuclear technologies.
>
> **(M3)** Life Cycle Analysis **LCA/LCIA-JRC** used by Joint Research Centre in the frame of the Taxonomy Regulation debate to assess the entire cycle of nuclear power.

The purpose of the first methodology is to evaluate a national or global nuclear energy system regarding its long-term sustainability according to the INPRO defined set of basic principles, user requirements and criteria; to identify the gaps in the assessment areas for existing or planned nuclear energy systems (NES) sustainability; and to recommend follow-up actions to close these gaps.

The second methodology is devoted to the comparison of the sustainability performance of different nuclear technologies or NES development scenarios.

The third methodology was developed in the context of the EU classification system ("EU Taxonomy") of environmentally sustainable economic activities which is established for the assessment of financial investments. **LCA/LCIA-JRC** aims to assess the nuclear sector considering the entire life cycle and to compare the sustainability performances of the most relevant energy production alternatives.

Before detailing characteristics of the three candidate methodologies, it may be useful to understand the general approach and how different stakeholders, experts, and policy-makers typically may be involved. The steps of the process followed by M1 and M2 are presented in Fig. 4.1.1.

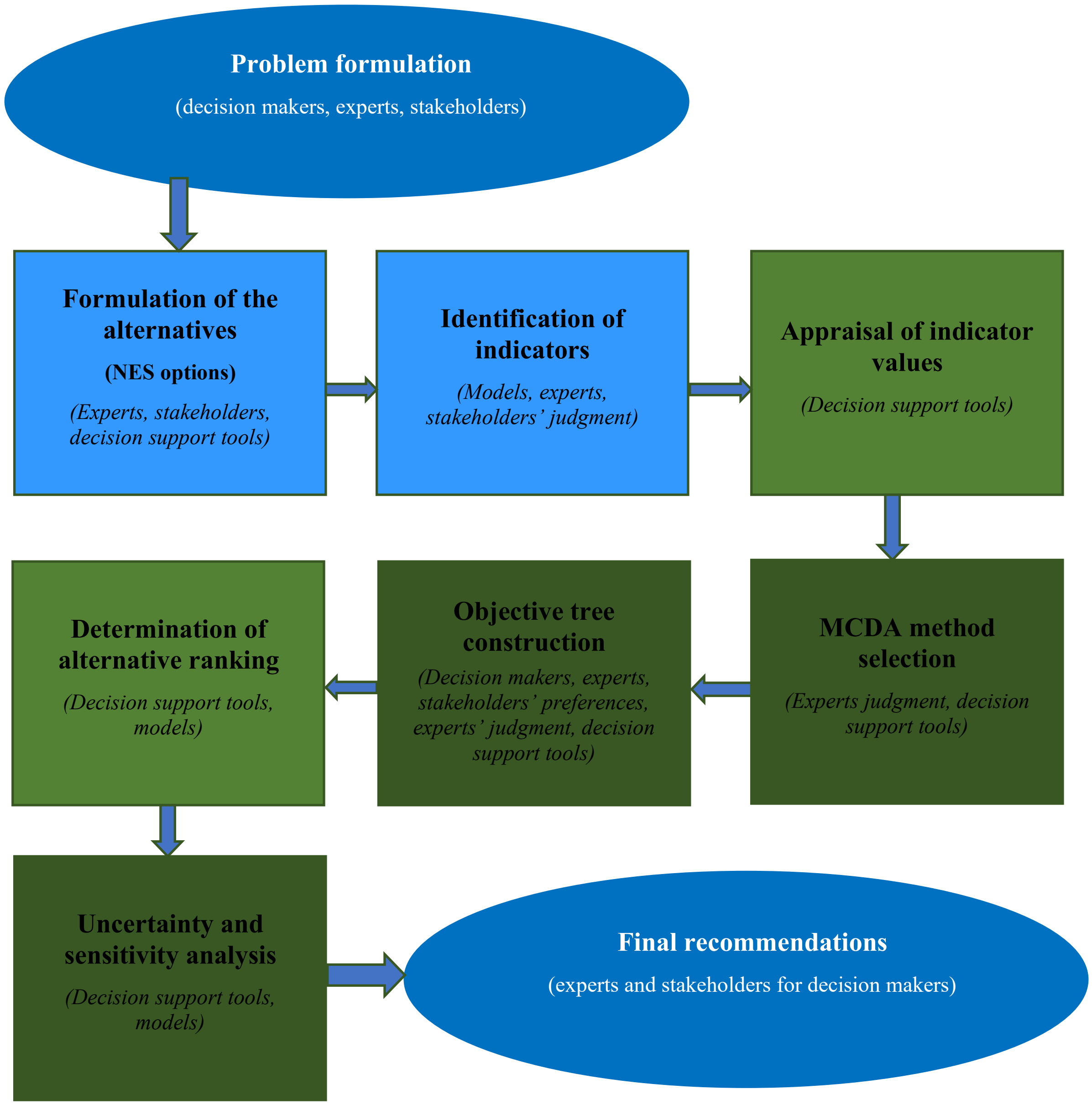


Fig. 4.1.1 Steps in conducting MCDA

The stakeholders play an important role in the initial steps (problem formulation, identification of alternatives, selection of the indicators). In the final step, stakeholders can contribute to overall interpretation and the formulation of recommendations targeting the decision-makers level.

In the ECOSENS project a discussion with the stakeholders was planned in order to identify a suitable methodology and/or to identify the valuable elements of each methodology considering the objectives of

ECOSENS assessment. For this purpose, an international workshop was organized in March 2023[3], for which the text of this Section 5 was presented to the participants in advance as background material. The participation of stakeholders is expected again in the final assessment step, to aid in interpretation of results.

.2 4.2. M1, MCDA - Nuclear Energy System Assessment (MCDA-NESA)

According to [31] Multiple-Criteria Decision Analyis (MCDA) is “an umbrella term to describe a collection of formal approaches which seek to take explicit account of multiple criteria in helping individuals or groups explore [complex] decisions that matter”.

To use MCDA, the decision-maker typically must [12], [31], [32]: identify the alternatives (the options submitted to decision); define the set of criteria (factors that will be used to evaluate the alternatives); assign weights to the criteria (criteria are usually ranked in order of importance, and the weights reflect this ranking); evaluate the alternatives; calculate the scores (the scores are calculated by multiplying the weights for each criterion by the alternative's performance); and select the best alternative.

Of note, the process may be targeted:

(i) to select the "best" alternative from the set of available alternatives (where the "best" means "the most preferred alternative" by the decision-makers), or

(ii) to obtain a small set of good alternatives.

In the case of M1, MCDA enables the analysts to search for compromises among the conflicting factors that determine Nuclear Energy System (NES) and Nuclear Fuel Cycle sustainability. M1 aims to assess NES capabilities to meet national sustainability requirements.

M1 consists of a set of **Basic Principles** (BPs), **User Requirements** (URs), and **Criteria** (CRs) together with the **assessment Areas** (Fig. 4.2.1). The methodology is applicable for existing and for a future NESs, including those with innovative components (such as new reactor technologies, or small modular reactors).

A Basic Principle (BP) is “a statement of a general goal to be achieved by nuclear technology and provides broad guidance for its deployment”.

The User Requirement (UR) is defined as “what should be done by designer, operator, industry and/or state to meet goal defined in Basic Principle”.

The Criteria (CR) consist of a set of relevant indicators and acceptance limits, together forming “the assessor’s tools to check whether a User Requirement has been met.”

The NESA structure is quite complex including 14 basic principles, 52 URs, and 125 criteria (Kuznetsov, 2015).

A NES is considered as sustainable **if all BPs shall be met** in the **areas** of: (A1) economics, (A2) infrastructure, (A3) waste management, (A4) proliferation resistance, (A5) physical protection, (A6) environment, (A7) safety. Specific BPs were developed where needed for these areas, resulting in a sum total of 14 BPs that can be considered in the sustainability assessment of the complete nuclear power cycle. In order to assess the entire cycle, BPs take into consideration all the steps: nuclear power generation, fuel fabrication, radioactive waste management and decommissioning.

[3] See the report [34] downloadable here: https://ecosens-project.eu/decarbonizing-europes-energysystem-check-ing-and-choosingindicators-for-a-sustainabilityassessment/

Fig. 4.2.1 Structure of NESA (Kuznetsov, 2015)

For each BP a set of user requirements is defined, consisting of conditions that should be met to achieve the corresponding basic principle. For each UR a set of criteria, enabling the judgment of NES potential, is identified and used for the assessment (Fig.4.2.2). Each INPRO criterion consists of an 'indicator' and an 'acceptance limit'.

A list of BPs used in NESA is presented in Annex 1. The BPs are formulated to include the development of Innovative Nuclear Systems (INS).

Two types of indicators are used to operationalize the INPRO criteria: (1) numerical (measured or calculated value of a property, for example the estimated probability of a major release of radionuclides to the containment obtained from combined deterministic and probabilistic analysis), (2) logical (usually associated with some necessary feature of a NES and usually presented in form of a question) [33].

Indicators may be based on single parameter, on an aggregated variable, on a status statement. Some indicators are applicable globally at the level of NES, other only for specific components (NPP, reactor), or for a specific technology (e.g. PWR, PHWR, etc.). Some indicators use "evaluation parameters" to determine whether or not the acceptance limit is met. In some cases when the parameters have their own acceptance limits, they are called sub-indicators.

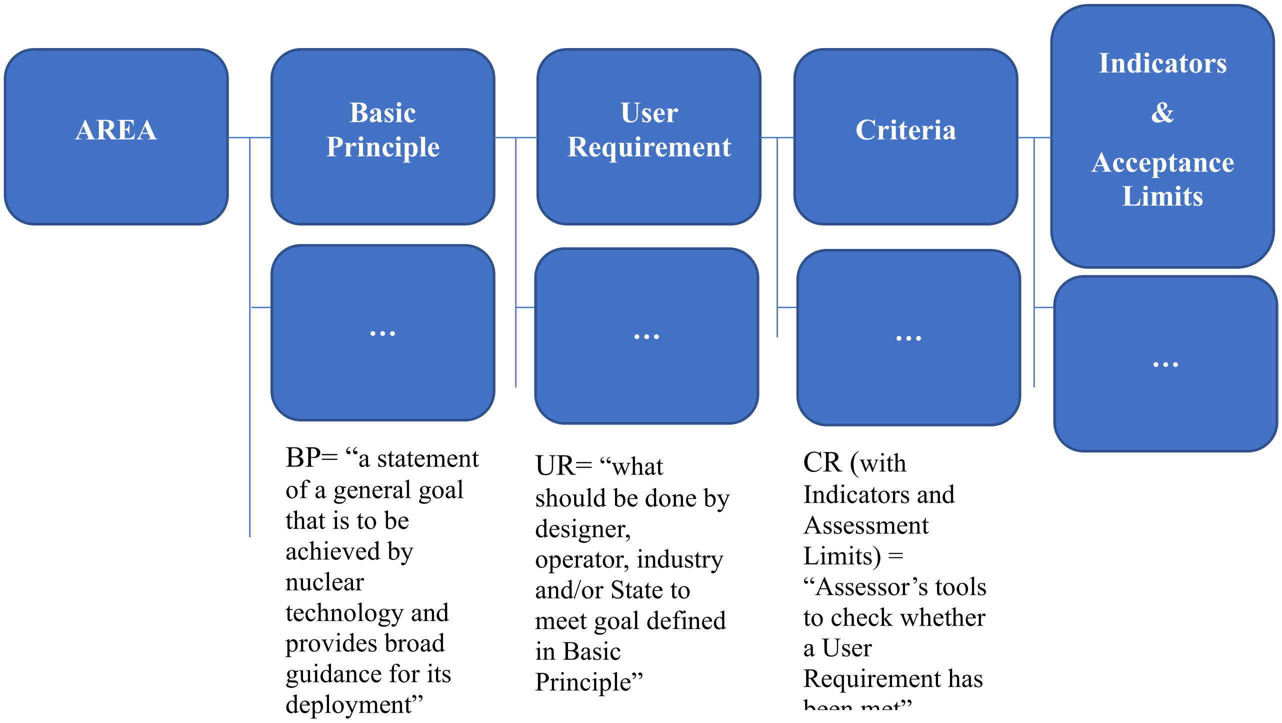


Fig. 4.2.2 Generic structure of assessment for a considered Area

.3 4.3. M2, MCDA-KIND

The second methodology under consideration, MCDA-KIND, was developed by the INPRO Collaborative Project KIND (Key Indicators for Innovative Nuclear Energy Systems, launched in 2014) to help decision makers analyze a finite number of alternatives by using a common set of indicators. In this way MCDA-KIND integrates the approach discussed above for M1, but simplifies the range of variables, and enables the introduction of new indicators or the adaptation of existing ones.

This feature is attractive for ECOSENS because it restrains the universe of decision options to a number that can reasonably be discussed by stakeholder workshop participants, and later be assessed under the project time constraints. On the other hand, the intention to use the methodology for a comparison of different energy alternatives involves the introduction of new indicators.

In M2, the approach begins with identifying a small number of **High-Level Objectives** (**HLO**) in terms of which the energy system will be judged. In a set of studies performed by some countries, presented in (IAEA_8, 2019), three HLO are used: (1) Cost (reflecting economic performance; the nuclear energy system should be competitive on the energy market); (2) Performance (integrating waste management, proliferation resistance, environment, and some possible country specifics); (3) Acceptability (reflecting the maturity of the technology, and acceptability at societal level).

The next level, **Area**, allows the grouping of indicators in a consistent sub-set. In [12] seven areas are used:

(A1) Safety,

(A2) Economics,

(A3) Waste management,

(A4) Proliferation resistance,

(A5) Environment,

(A6) Maturity of technology,

(A7) Country specifics.

By contrast with the NESA methodology presented in the previous section, the KIND methodology does not approach directly the Infrastructure and the Physical protection areas. A6, Maturity of technology, uses an aggregated risk measure yielding a comparative evaluation of less and more mature options which may then be interpreted for decision makers. A7, Country specifics, was additionally introduced to offer the possibility to adapt the methodology to certain national characteristics such as those reflected in national strategic documents. In this way, MCDA-KIND offers more flexibility in adaptation to country specifics in comparison with NESA.

The third level of KIND methodology consists of a set of specific **Key Indicators (KIs)** which show how a given system performs in a particular area. KIs are converted (by stakeholder or expert judgment) into scores to enable comparison of the performance of different technologies, scenarios, or NESs. The conversion uses a scale, for example from 1 to 10.

Generally, a comparative assessment of technologies, scenarios, or NESs is performed with reference to a set of high-level objectives. These are defined by the experts and stakeholders involved in the assessment, who then select areas to be grouped respectively under each HLO.

The comparison is conducted at the level of each area. Here, for each KI a weight should be determined, based on the prioritization of the KIs within the given area (again, by stakeholder or expert judgment, and with reference to HLO). A score per area is obtained by summing the weighted contribution of each KI. A schematic view is presented in Fig. 4.3.1.

The score may be used to compare the performances of different technologies in a specific area or for an overall comparison of some NESs or technologies. In this last case. a secondary weighting (performed this time among areas) is necessary to produce the global outcome score.

KIND methodology employs both quantitative KIs (physically measurable and expressed by a number) and qualitative KIs (appraised by stakeholder or expert judgment or perception).

- For quantitative KIs the starting point is to measure and record both the acquired value and the associated accuracy of that measurement. After that, the measurement is converted using a ‘value/utility function’ and MCDA methods in order to output a value of the KI on a standard scale (e.g. 0–10). The scale may be linear (most commonly used) or non-linear (when a threshold value is present).
- Non-measurable indicators, called qualitative, subjective or non-quantified KI, are assigned primary values by collecting appraisals from several experts or other stakeholders. There are several ways to perform the conversion, one being to average subjective appraisals and to convert the average figure using the same linear or non-linear scale.

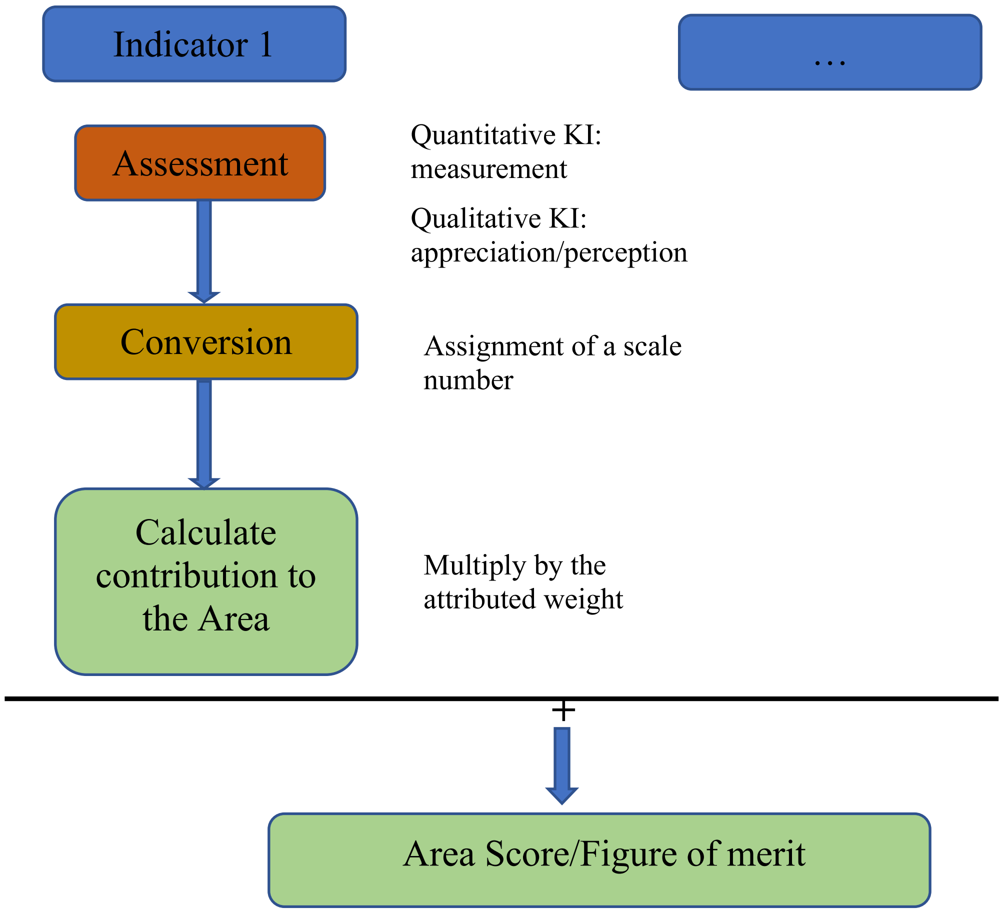


Fig. 4.3.1 Assessment of the KIs and conversion into the score

In Fig. 4.3.2 a schematic view of the structure of HLO, areas and indicators are presented.

Overall, M2 has the advantage of simplicity. The most onerous effort is to handle the diversity of opinions, especially for settling the weighting factors. For example, there may be a diversity of appraisal among the involved experts and stakeholders regarding the weight (importance) to be assigned to certain indicators, or to the overarching area. Such diversity could stem from factors of differing type or order. For instance, the various expert/stakeholder judges may diverge in their societal values; or in their understanding of the required range of sub-indicators; or in their views on the extent or accessibility of existing knowledge, or on the confidence to be assigned to future acquired figures. Such factors should be brought to light by discussion, and compromises sought.

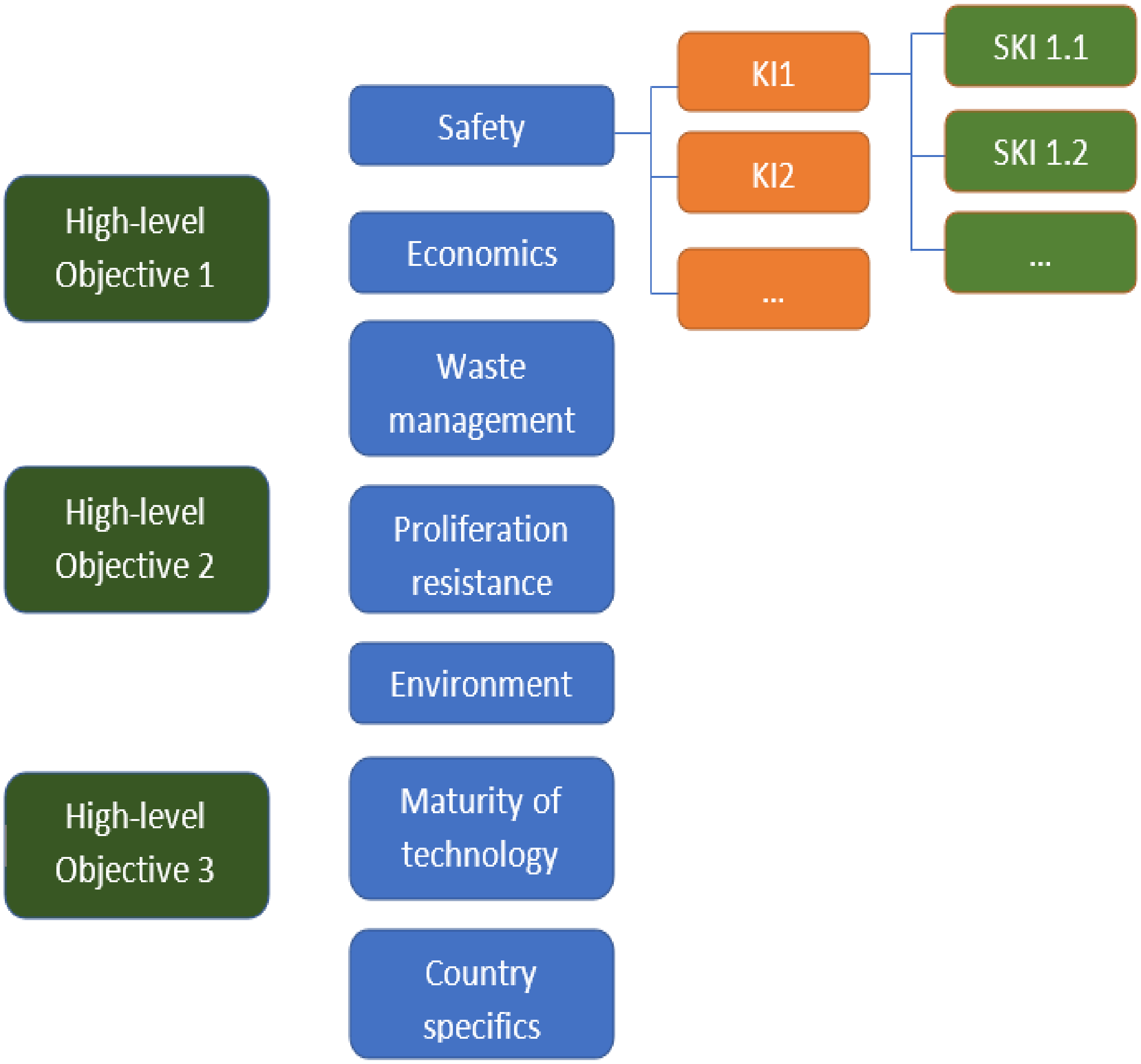


Fig. 4.3.2 MCDA-KIND, schematic view of the approach

For quantitative KIs the starting point is to measure and record both the acquired value and the associated accuracy of that measurement. After that, the measurement is converted using a '**value/utility function**' and using MCDA methods in order to produce a value of the KI on a standard scale (e.g. 0–10). The scale may be linear (most commonly used) or non-linear (when a threshold value is present).

Non-measurable indicators, called qualitative, subjective, or non-quantified KI, are assigned primary values by collecting appreciations from several experts or other stakeholders. There are several ways to perform the conversion. One of them is to average different subjective appreciations and to convert this using the same linear or non-linear scale.

After that, a figure of merit is sought. This is achieved by combining the different converted values of KIs according to a weighting approach, which engages stakeholder judgement.

The weighting factors approach defines a relative importance of each indicator (w_i), with the constraint:

$$\sum_{i=1}^{N} w_{j,i} = 1$$

where N=number of the indicators included in an area.

In parallel, weighting is applied for the areas grouped by stakeholders into a high-level objective:

$$\sum_{j=1}^{M} w_j = 1$$

where M=number of the areas included in the high-level objective.

Based on the weighting factors a function objective is constructed as:

$$u(x) = \sum_{j=1}^{M} w_j \sum_{i=1}^{N} w_{j,i}\, x_i$$

The comparison of two (or more) technologies, systems, or NESs may be performed based on the values of the function $u(x)$.

An assessment example is presented below. For a comparative analysis of a set of nuclear technologies, performed by the Romanian team collaborating in INPRO KIND [12], the following high-level objectives were considered (Fig. 4.3.3):

(1) Cost,

(2) Performance,

(3) Acceptability.

The Cost objective engages a single area: Economics (E).

The Performance objective engages four areas: Waste management (WM), Proliferation resistance (PR), Environment (ENV), Safety (S).

The Acceptability objective engages two areas: Maturity of technology (M), and Country specifics (CS).

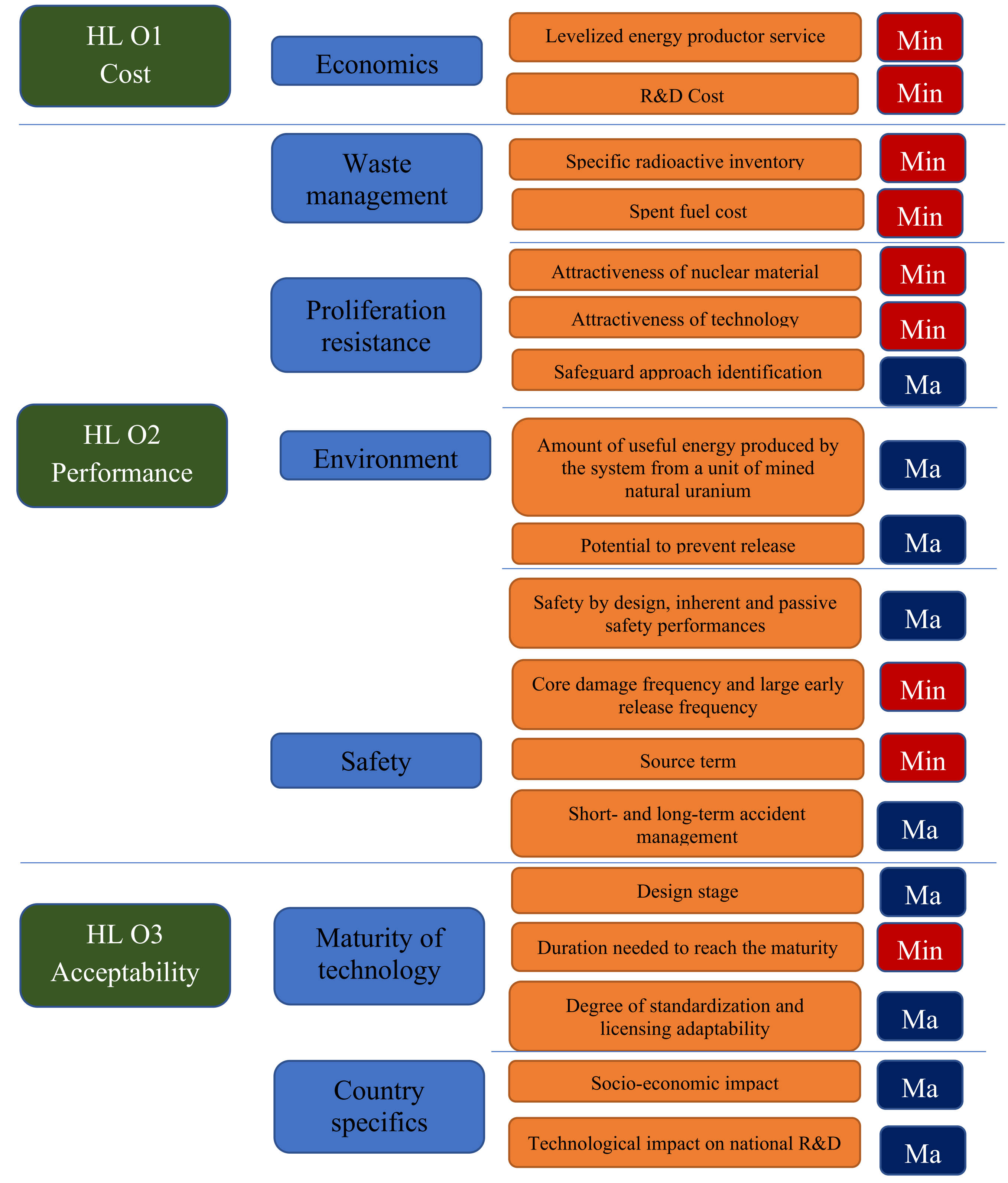


Fig. 4.3.3 Example of elements used in a MCDA-KIND to compare different technologies

.4 4.4. M3, LCA/LCIA

LCA (Life Cycle Analysis) was developed in the 1960s in connection with concerns on environmental impacts, aiming to provide a comparison between alternative products. The main goal of LCA is to assess the potential environmental impacts of an activity or of a product, taking into account all phases of production and use across the entire life cycle. LCA may help decision makers to compare different products (or processes/actions) and to select the appropriate one from the point of view of environmental impact and human health.

In the ISO 14040:2006 standard (*Environmental management- Life cycle assessment- Principles and framework*) the approach is characterized by 4 obligatory steps (Fig. 4.4.1).

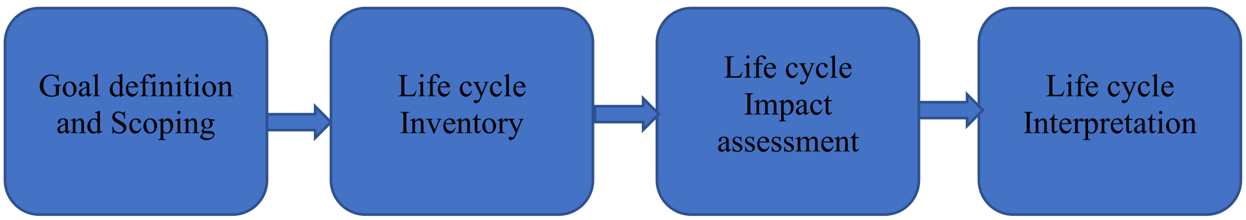


Fig. 4.4.1 Obligatory steps in LCA

In the first step, Goal definition and Scoping, the purpose of the assessment, the method, and the system boundaries, together with the data requirements and organization of the results, are defined.

The second step, Life cycle Inventory, is devoted to collecting all relevant data such as the flow of materials, energy, emissions, and waste. The data will include information on forms of human health and environmental impact.

In the third step, Impact assessment, the potential impact on human health and environment, as well as estimated resource depletion, is calculated. In ISO 14040:2006 the step is formalized in four sub-steps (of which only the first two are mandatory):

(1) selection and classification of the relevant impacts according to the impact categories,

(2) characterization of the potential impact using science-based conversion factors,

(3) normalization of the potential impacts in a manner that allows comparison,

(4) weighting and/or ranking of the different environmental impact categories reflecting the relative importance of the impacts considered in the study.

The final step, Interpretation, is devoted to analysis and results interpretation. A set of conclusions or recommendations is produced. The analysis will include also the assumptions and data (including engineering estimates), sensitivity analysis, consistency check, limitations, and constraints of the analysis.

LCA can offer a holistic view on the entire lifespan of a product or a process and allows the identification of the key issues influencing environmental and health impact. In order to deepen and detail knowledge of impacts at step 2, LCIA (Life Cycle Impact Assessment) may be used. Here the impacts are divided into impact categories, the most common being the following set of 12: climate change, ozone depletion, photochemical ozone formation, respiratory inorganics, ionizing radiation, acidification, eutrophication, human toxicity, ecotoxicity, land use, water use, and resource depletion. These categories enable the grouping of some inventories (Table 4.4.1).

Table 4.4.1 Grouping of inventories in common impact categories (JRC, 2021)

Impact category	Examples of inventories
Climate change	Carbon Dioxide (CO2) Nitrogen Dioxide (NO2) Methane (CH4) Chlorofluorocarbons (CFCs)
Stratospheric ozone depletion	Chlorofluorocarbons (CFCs) Hydrochlorofluorocarbons (HCFCs) Halons Methyl Bromide (CH3Br)
Photochemical smog	Non-methane hydrocarbon (NMHC)
Particulate Matter/ Respiratory inorganics	Sulphur Dioxides (SO2) Nitrogen Oxides (NOx) Solid and liquid particulates Non-methane volatile organic compounds (NMVOC)
Ionizing radiation, human health	Routine atmospheric and liquid releases in the nuclear fuel cycle
Ionizing radiation, ecosystems	Radioactive releases to freshwater and its sediments
Acidification	Sulfur Oxides (SOx) Nitrogen Oxides (NOx) Hydrochloric Acid (HCL) Hydrofluoric Acid (HF) Ammonia (NH4)
Eutrophication	Phosphate (PO4) Nitrogen Oxide (NO) Nitrogen Dioxide (NO2) Ammonia (NH4)
Human Toxicity	Total releases to air, water, and soil
Terrestrial Toxicity	Toxic chemicals with a reported lethal concentration to rodents
Aquatic Toxicity	Toxic chemicals with a reported lethal concentration to fish
Land use	Quantity disposed of in a landfill or other land modifications
Water Use	Water used or consumed
Resource depletion	Quantity of minerals used Quantity of fossil fuels used

The inventories are estimated based on quantitative models, using computing tools and input data. In order to perform the assessment, each inventory must be converted into representative indicators determining impact scores. Two kinds of impact indicators are used:

a. Mid-point indicators characterize the contributions of the inventory to the different environmental effects at some intermediate point in the cause-effect chain.

b. End-point indicators assess the actual damage resulting from these contributions (JRC, 2021).

The final sub-step within Impact assessment, weighting, consists of the assignment of relative weights to each impact category, producing thus a ranking according to the perceived relevance or importance of each category. Although it is identified as optional, the weighting sub-step is very useful in case of comparison of different alternatives. Weighting offers an opportunity to collect and discuss stakeholder judgments.

As an example, in [13] the LCIA method was used to assess the nuclear sector in the context of developing the EU Taxonomy of environmentally sustainable economic activities. In step one, six environmental objectives were selected:

(1) climate change mitigation,

(2) climate change adaptation,

(3) the sustainable use and protection of water and marine resources,

(4) the transition to a circular economy,

(5) pollution prevention and control,

(6) the protection and restoration of biodiversity and ecosystems.

Also in step one, it was decided to bound the scope of the assessment to encompass the following Life Cycle components:

(1) uranium mining and uranium ore processing,
(2) conversion to uranium hexafluoride (UF6) gas,
(3) enrichment of uranium,
(4) fabrication of UO2 nuclear fuel,
(5) reprocessing of spent nuclear fuel,
(6) production of MOX fuel,
(7) nuclear power plant operations (this includes construction, electricity generation and long-term operation of NPPs, as well as NPP decommissioning and site remediation),
(8) management and disposal of radioactive and technological waste.

Steps two and three were carried out using the above discussed impact categories and inventories. Step four, interpretation, and recommendation, yielded recommendations reflected by integrating nuclear energy production into the Taxonomy.

Most part of the indicators of the previous study are very useful to assess the Environmental pillar of sustainable development in ECOSENS project.

.5 4.5 Comparison of the methodologies

.5.1 4.51. Selection criteria (SC)

This section includes aspects discussed by the ECOSENS stakeholder workshop of 30 March 2023 [34].

A set of criteria for the selection was proposed to the participants to select the most suitable methodology, or to recommend a combination of methods, to be used in ECOSENS. The selection criteria (SC) were developed with an awareness of the different qualifications and skills to be present in the 30 March 2023 workshop. The workshop, entitled "Decarbonizing Europe's energy system: Checking and choosing indicators for a sustainability assessment" brought together people experienced in modelling of energy systems (or in sustainability or other assessments) or holding some other expertise relevant to energy transition topics.

On the other hand, the following selection criteria (SC) were developed and used by the authors of current deliverable previously to the workshop. A pre-decision-in-principle was produced to combine and employ elements of M2 (MCDA-KIND-IAEA) and M2 (LCA/LCIA-JRC).

The same SC are proposed to form the basis for the workshop discussion of the qualities or weak points of the three considered methodologies, and eventually validation of the pre-decision-in-principle:

- (SC1) Compliance with the planned resources,
- (SC2) Relevance for the objectives of the research,
- (SC3) Enabling treatment of the entire life cycle,
- (SC4) Enabling inter-comparison of different technologies,
- (SC5) Availability of requested data (including possibility to generate),
- (SC6) Adaptability (to include specific requirements, for example modelling the evolution of the technologies and energy market),
- (SC7) Suitability to assess performance at regional (European) level,
- (SC8) Suitability to the involvement of a large group of stakeholders for certain assessment steps.

Definition of the proposed selection criteria is offered below to support understanding during the stakeholder workshop discussion.

(SC1) Compliance with the planned resources:

- (i) The assessment performed by ECOSENS staff should be finalized in September 2024,
- (ii) The estimated effort will not exceed 18 person-months.

(SC2) Relevance for the objectives of the research:

The methodology will be able to assess the sustainability of nuclear power for the entire life cycle considering the current development of nuclear technologies. In addition, it should have the capabilities to investigate the evolutions of the energy market in the transition toward climate neutrality and discuss the role of nuclear power in the medium and long term.

(SC3) Enabling treatment of the entire life cycle:

The methodology can take into consideration all the life cycle phases of nuclear power units covering the entire fuel cycle (mining, enrichment, fuel fabrication, reprocessing, radioactive waste disposal) and all stages of development (design, siting and licensing, operation, decommissioning and site remediation).

(SC4) Enabling inter-comparison of different technologies:

The methodology will have enough generality to allow an inter-comparison of different energy alternatives (at least nuclear, gas, hydro, photovoltaic, and wind).

(SC5) Availability of (including possibility to generate) requested data:

A sufficient quantity and/or range of requested data, to a manageable level of complexity, will be available and accessible in literature, official reports, etc., and/or it is possible to acquire needed data or to generate it by using available models.

(SC6) Adaptability (to include specific requirements, for example modelling the evolution of the technologies and energy market):

The methodology will be adaptable to the assessment of the future generation of nuclear systems, with extra value assigned for ease of adaptation to evolving technologies.

(SC7) Suitability to assess performance at regional (European) level:

The methodology will have been demonstrated for use at regional level or is judged to have enough potential to be applied for regional-level assessment.

(SC8) Suitability to the involvement of a large group of stakeholders:

The methodology will be amenable to participation by a broad spectrum of stakeholders, and the criteria and indicators it deploys are amenable to judgment by stakeholders of different roles and disciplinary backgrounds.

.5.2 4.5.2 Comparison of the methodologies

The participants in the International Stakeholder Workshop [34] were invited to compare the three above presented methodologies based on the set of criteria presented in the previous section.

Worksheets were available in the format presented in Table 4.5.2.1. A scale of 0 to 3 (*does not fulfil – entirely fulfils)* was proposed in regard to each selection criterion. A working paper presenting the methodologies was distributes to all the participants in advance (two weeks before the workshop). Additionally, the three methodologies were presented in the first part of the workshop.

Table 4.5.2.1 Table to collect individual stakeholder judgments on SC1-8, using a scale of 0 to 3

Selection Criteria	Method		
	M1, MCDA-NESA-IAEA	**M2, MCDA-KIND-IAEA**	**M3, LCA/LCIA-JRC**
SC1			
SC2			
SC3			
SC4			

SC5			
SC6			
SC7			
SC8			
Averaged Column Score			

A detailed discussion of the exercise is presented in the report dedicated to the workshop [34].

Only a part of the participants succeeded to complete this scoring. The results are presented in Table 4.5.2.2. The outcome upon calculation of the averaged scores confirmed the pre-decision-in-principle to combine M2 and M3, method M1 seems to be too complex and not well adapted to ECOSENS purpose and resources

Table 4.5.2.2 Averaged answers from participants in the international workshop [34]

INDIVIDUALS	**Method**		
	M1, MCDA-NESA-IAEA	**M2, MCDA-KIND-IAEA**	**M3, LCA/LCIA-JRC**
1	0.875	2.375	2.75
2	2.3	2.44	1.6
3	1.75	2	2.75
4	1	1.375	2.75
5	0.875	2	1.875
6	1.625	1.875	1.5
7	-	-	2
Average	**1.40**	**2.01**	**2.18**

.6 4.6. Proposed methodology

ECOSENS aims to perform a LCA (Entire life cycle assessment) for nuclear power at the present day and at European level, taking into consideration the current share of nuclear generated electricity and the current status of nuclear technology. The finalization of the assessment of the nuclear energy is planned for September 2024. It has to be noted the assessment of nuclear will be performed in the context of short-term (at the level of 2035) and considering the existing perspective of EU policies on the energy mix.

Another effort will be devoted to the development of energy scenarios including possible shares of nuclear energy in the medium to long term will be performed, with the overall goal set as attaining a decarbonized Europe. This prospective assessment will integrate and compare the sustainability performances of energy alternatives and will be presented in a separate deliverable. The energy mix scenarios will include nuclear, renewables (especially PV, wind, and hydro), and gas technology. The intention is to have a fair discussion of the impacts (advantages and disadvantages) of these technologies and their combination, in the context of future energy markets (or demand contexts). The interpretation stage should identify gaps between desired and projected performances, and introduce some recommendations for both energy systems and technology developments. Thus, the ambition of the work is to demonstrate a methodology applicable for assessing energy alternatives on the future market (or in a future demand context), amenable to discussion and influence by stakeholders. Due to the limited resources of the ECOSENS project, the detailed demonstration use of the methodology will be focused on nuclear and short-term evolutions.

As discussed above, based on the previous comparison of methodologies, a pre-decision-in-principle selected a combination between M2 (MCDA-KIND) and M3 (LCA/LCIA-JRC). From M2 the assessment based on weighted scores is selected as a valuable element, and from M3 the approach of the entire life cycle.

LCA generally considers three main phases of a product/service/technology (Fig. 4.6.1): production, use/operation, and end-of-life/decommissioning, including the potential for recycling. For energy technologies, production consists of sub-phases such as the production of the equipment and its components, fuel, etc., plus the construction process finalized by the commissioning step. An extensive analysis may furthermore include the applied part of the RDI efforts.

The ECOSENS assessment is proposed to appraise indicators characterizing the typical pillars of sustainable development, thus structuring the LCA in three chapters:

(1) En-LCA, Environmental life cycle assessment,

(2) Ec-LCA, Economic life cycle assessment,

(3) So-LCA, Social life cycle assessment.

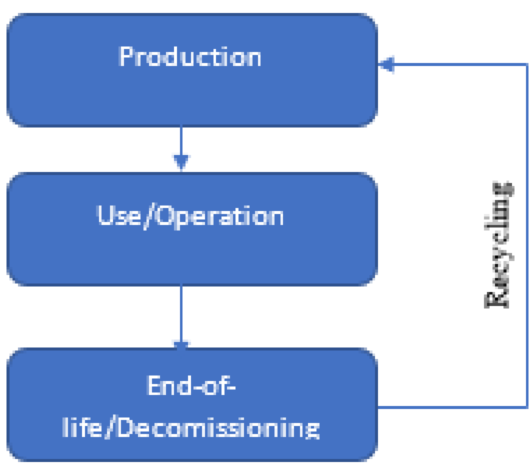


Fig. 4.6.1 The main phases considered in LCA

During the International Stakeholder Workshop [34], the participants were invited to propose the High-Level Objectives (HLOs), one for each of the above presented chapters.

The debate around HLOs reflected a diversity of opinions [34] on the selection of a HLO with a lack of convergence of the positions, influenced by the short time of the exercise. However, the debate inspired a post-workshop definition of the HLOs as:

(1) Environmental, HLO: "Contribution to planetary wellbeing",

(2) Economic, HLO: "Reliability and resilience of supply",

(3) Social, HLO: "Social feasibility".

The discussion on the indicators reflected different opinions [34]: from drastically simplification (minimize the number of indicators) to keep as detailed as possible the indicators presented in order to support a fair assessment. There were no opinions clearly formulated to eliminate certain indicators. In such conditions, the solution was to keep all indicators and sub-indicators and to use the capability of the weighting process to eliminate those indicators considered by the participants as irrelevant.

In Table 4.6.1 the indicators proposed for En-LCA are presented together with some sub-indicators aimed to support a complete interpretation and a fair assessment of a certain indicator.

Table 4.6.1 Indicators (and sub-indicators) for En-LCA (Environment)

Indicator	Sub-indicators
1.1 Carbon emissions	-
1.2 Land occupation and power density	-
1.3 Energy returned on investment	-
1.4 Impact on resources	1.4.1 Operational water consumption
	1.4.2 Abiotic resources depletion
	1.4.3 Depletion of fossil fuels
	1.4.4 Excessive use of resources useful for the life sustaining
	1.4.5 Exhausting of rare resources
1.5 Potential material recyclability	-
1.6 Emissions (other than C)	1.6.1 NOx and SO2 emissions
	1.6.2 Ozone depletion potential
	1.6.3 Photochemical oxidant creation potential
	1.6.4 Cumulative lifecycle emissions of NMVOC and PM2.5
1.7 Impact on life and ecosystems (under normal operation)	1.7.1 Human toxicity potential
	1.7.2 Human health/mortality impact
	1.7.3 Ecotoxicity
	1.7.4 Acidification and eutrophication potential
	1.7.5 Freshwater ecotoxicity
	1.7.6 Marine ecotoxicity
	1.7.7 Biodiversity of the used land

1.8 Impact of generated wastes	1.8.1 Chemical (generated) waste volumes
	1.8.2 Radioactive wastes (generated)
	1.8.3 Maturity of the approach (experience and effectivity in waste management)
	1.8.4 Long-term effect of deposited wastes
1.9 Impact of accidental situations	1.9.1 Impact of the accidents (anticipated, design base)
	1.9.2 Impact of severe accidents (considering mitigation/prevention)
1.10 Mitigation of accidents	1.10.1 Inherent safety
	1.10.2 Passive systems
	1.10.3 Safety by design

In Table 4.6.2 the indicators sub-indicators proposed for Ec-LCA are presented.

Table 4.6.2 Indicators (and sub-indicators) for Ec-LCA (Economics)

Indicator	Sub-indicators
2.1 Capacity factor	-
2.2 Global efficiency	-
2.3 Cost	2.3.1 Cost of the investment (capital cost)
	2.3.2 Cost of operation (including fueling and maintenance)
	2.3.3 Cost of decommissioning (including environmental remediation)
2.4 Cost for system integration	2.4.1 Maneuverability
	2.4.2 Load following
	2.4.3 Stability
	2.4.4 Easy to be integrated in local/regional grids
	2.4.5 Realistic solution for large scale storage
2.5 External costs	-
2.6 LCOE	-
2.7 Macro-economic impact	-
2.8 Applicability for cogeneration	-
2.9 Level of standards generated, rules and control	2.9.1 Maturity of the authorization process
	2.9.2 Level of industrial codes and standards
	2.9.3 Needs for technical support

In Table 4.6.3 the indicators and sub-indicators proposed for So-LCA are presented.

Table 4.6.3 Indicators (and sub-indicators) for So-LCA (Social)

Indicator	Sub-indicators
3.1 Jobs created	3.1.1 Direct high-education jobs
	3.1.2 Jobs in contributing industries

3.2 Impact on the local/regional business (partner with other business)	-
3.3 Additional goods and services created	-
3.4 Value of the knowledge generated and maintained for the future	-
3.5 Impact on education	-
3.6 Contribute to the reduction of inherited burdens (toxic wastes, military stocks)	-
3.7 Impact on health improvement	-
3.8 Impact on poverty	-
3.9 Societal-level adoption of the technology	-
3.10 Existing investment in RDI to develop the technology	-
3.11 Dependency on government support (funding or incentives, such as tax credits or subsidies)	-
3.12 Risks	3.12.1 Level of risk reflected in insurance needs
	3.12.2 Proliferation of sensitive materials
3.13 Equality of opportunities	3.13.1 Women's empowerment
	3.13.2 For minorities, vulnerable social groups, Indigenous peoples, children, people with disabilities

The weighting process is a crucial step consisting of assigning relative importance or weights to the indicators (and sub-indicators) to reflect their significance in the final figure of merit.

As it was mentioned earlier the weighting process may eliminate some indicators or sub-indicators if zero weight (or very low values) will result from the assigning step. Technically there are various methods for assigning weights to criteria such as: (1) subjective weights (stakeholders or decision-makers assign weights based on their judgment and expertise), (2) pairwise comparison (stakeholders compare criteria against each other and provide relative importance judgments), (3) mathematical optimization (using mathematical techniques to optimize weights based on predefined objectives or constraints), (4) data-driven methods (using historical data or statistical analysis to derive weights).

In ECOSENS methodology, taking into consideration the ambitious of a large participation of the stakeholders, the weighting will be performed by using the subjective weights approach.

Once the weights are assigned, they are often aggregated to create an overall value or score for each alternative. Aggregation methods can include weighted sum, weighted product, or more complex methods (TOPSIP [35], ELECTRE [36]). In ECOSENS methodology the weighted sum will be used.

In should be mentioned that the methodology may be improved by sensitivity analysis. After the weights are assigned and the alternatives' scores are calculated, it's important to perform sensitivity analysis. This helps to assess how sensitive the final figure of merit is to changes in the assigned weights. It provides insights into the robustness of the decision-making process.

The proposed methodology involves a threefold weighting:

(1) at the level of the indicator (considering the set of existing sub-indicators),

(2) at the level of HLO,

(3) at the level of an energy technology.

Considering *N_Sj*=number of sub-indicators for the indicator indexed by *j, N_Ik*=the number of indicators for the HLO indexed by *k*, and *N_H*=number of HLOs we'll have:

$$S_{global} = \sum_{k=1}^{N\_H} (w\_H_k \sum_{j=1}^{N\_Ik} (w\_in_j \sum_{i=1}^{N\_Sj} (w\_si_i * S\_Si_i)))$$

where S_Si_i is the score assigned by the evaluators to the sub-indicator *i* (of the indicator *j*), w_si_j is the weight for the sub-indicator *i*, w_in_j is the weight for the indicator *j* (of the HLO indexed by *k*), and S_{global} is the final score (the figure of merit for an assessed energy technology.

Each set of weights (at the level of indicators, HLO, and energy technology are normalized to 1.

$$\sum_{k=1}^{N\_H} w\_H_k = 1, \quad \sum_{j=1}^{N\_Ik} w\_in_j = 1, \quad \sum_{i=1}^{N\_Sj} w\_si_j = 1$$

During the International Stakeholder Workshop [34], an exercise was dedicated to gather input from the stakeholders. The developers of the methodology considered the stakeholders can provide insights based on their expertise and perspectives on the energy system. The participants were invited to attribute weights as an expression of their views on the prioritization of the sub-indicators and indicators.

Unfortunately, the weighting was a real challenge for many of the participants. Some of them mentioned a perception of personal insufficient knowledge, other the short time for the exercise, and few considered it is not the role of stakeholders to generate the weights.

To extract some valuable elements, form the answers, a reference case was defined simply having equal weights for the three sections, therefore 1/10 for Environment, 1/9 for Economics, and 1/13 for Social.

For simplicity, the weights assigned by stakeholders to different indicators/sub-indicators were expressed in percentage, with the normalization to 100%. The appreciations were averaged per each indicator and sub-indicator and the averaged value was compared with the reference case.

For some indicators there is a tendency to attribute a higher priority compared with the reference case:

(1) indicator 3.2, Impact on the local/regional business (partner with other business), with +115% (compared with the reference case),

(2) indicator 2.3, Cost, with +62%,

(3) indicator 2.4, Cost for system integration, with +62%,

(4) indicator 3.7, Impact on health improvement, with +56%,

(5) indicator 3.1, Jobs created, with +50%,

(6) indicator 1.1, Carbon emissions with +50%,

(7) indicator 2.7, Macro-economic impact, with +26%,

(8) indicator 1.4, Impact on resources with +20%.

For other indicators less priority than in the reference case was attributed:

(1) indicator 3.6, Contribute to the reduction of inherited burdens (toxic wastes, military stocks), with -48%,

(2) indicator 3.9, Societal-level adoption of the technology, with -48%,

(3) indicator 3.10, Existing investment in RDI to develop the technology, with -48%,

(4) indicator 2.1, Capacity factor, with -37%,

(5) indicator 2.8, Applicability for cogeneration, with -37%,

(6) indicator 3.4, Value of the knowledge generated and maintained for the future, with -35%,

(7) indicator 3.11, Dependency on government support (funding or incentives, such as tax credits or subsidies), with -35%,

(8) indicator 2.9, Level of standards generated, rules and control, with -28%,

(9) indicator 3.3, Additional goods and services created, with -22%,

(10) indicator 3.13 Equality of opportunities, with -22%,

(11) indicator 1.3, Energy returned on investment with -20%,

(12) indicator 1.10, Mitigation of accidents with -20%.

The values for all indicators are presented in the Table 4.6.4

Table 4.6.4 Results from the weighting exercise (averaged value, normalized)

		Stakeholders (average value of 6 participants) [%]	Average, normalized to 100% and rounded [%]	Deviation from equal distribution
En-LCA	1.1 Carbon emissions	15	**15**	+50%
	1.2 Land occupation and power density	8.75	**9**	-10%
	1.3 Energy returned on investment	8.33	**8**	-20%
	1.4 Impact on resources	12.08	**12**	+20%
	1.5 Potential material recyclability	8.33	**8.5**	-15%
	1.6 Emissions (other than C - Carbon)	8.33	**8.5**	-15%
	1.7 Impact on life and ecosystems (under normal operation)	10.83	**11**	+10%
	1.8 Impact of generated wastes	10	**10**	0%
	1.9 Impact of accidental situations	9.58	**10**	0%
	1.10 Mitigation of accidents	7.91	**8**	-20%
		99.14	**100**	
	2.1 Capacity factor	6.25	7	-37%

Eco-LCA	2.2 Global efficiency	8.75	9	-19%
	2.3 Cost	17.5	18	+62%
	2.4 Cost for system integration	17.5	18	+62%
	2.5 External costs	8.75	9	-19%
	2.6 LCOE	10	10	-10%
	2.7 Macro-economic impact	13.125	14	+26%
	2.8 Applicability for cogeneration	6.875	7	-37%
	2.9 Level of standards generated, rules and control	7.5	8	-28%
		96.25	100	
Soc-LCA	3.1 Jobs created	11.67	11.5	+50%
	3.2 Impact on the local/regional business (partner with other business)	16.67	16.5	+115%
	3.3 Additional goods and services created	6.33	6	-22%
	3.4 Value of the knowledge generated and maintained for the future	5	5	-35%
	3.5 Impact on education	6.67	7	-9%
	3.6 Contribute to the reduction of inherited burdens (toxic wastes, military stocks)	4	4	-48%
	3.7 Impact on health improvement	11.67	12	+56%
	3.8 Impact on poverty	10	10	+30%
	3.9 Societal-level adoption of the technology	4.33	4	-48%
	3.10 Existing investment in RDI to develop the technology	4.33	4	-48%
	3.11 Dependency on government support (funding or incentives, such as tax credits or subsidies)	5	5	-35%
	3.12 Risks	8.67	9	17%
	3.13 Equality of opportunities	5.67	6	-22%
		100.01	100	

From the discussion on the weighting exercise, three main positions of the participants should be noted:

(1) a group of stakeholders considered the lack of personal experience/knowledge for some indicators/sub-indicators produced discomfort in assigning realistic values

(2) another group perceived the pressure of time, the time dedicated to the exercise was short in comparison with the complexity of the methodology (in total 62 indicators and sub-indicators to receive weights)

(3) few stakeholders said the weighting process is a duty of the policy-makers directly interested in the assessment and not of the stakeholders representing the civil society.

Based on these positions, the developers of the ECOSENS methodology consider the weighting should be associated with the assessment context, mainly with the requirements of the beneficiaries clearly linked with a set of policies to be implemented. This decision does not exclude a weighting process with a large participation of the civil society.

The preparation of the assessment step will produce:

- the weights for sub-indicators, indicator and HLOs,
- the identification of the participants to the assessment,
- appropriate guidance for the assessment.

The ECOSENS methodology has the ambitious to involve a real participation of the stakeholders both in the construction and implementation of it.

In order to compensate the possible lack of knowledge and to help such group of stakeholders all the indicators and sub-indicators will be described in a small document based on collecting relevant data and information from official documents, scientific reports, research papers. The small document will be referred as the Fiche of the indicator/sub-indicator. A total number of 72 fiches are considered as part of the ECOSENS methodology (29 fiches for Environment, 17 for Economics, and 16 for Social).

In Fig. 4.6.1 the Fiche for the indicator 1.1 Carbon emission is presented.

Fiche – summary of data and considerations

Category of LCA assessment	Environment
Indicator	Carbon emissions
Sub-indicator	-
Date of release	2023 January 10
Responsible partner	RATEN ICN
Contributing organizations	-
Authors	M. Constantin
Version	1.0

The following data are compiled from (UNECE, 2021).

The carbon emission is calculated for entire life cycle of each technology, based on available data for the year 2020.

The indicator is presented in grams of CO_2 released for 1 kWh of electricity produced by the technology.

Nota bene, the data does not consider the carbon produced for the balancing of the energy system (for example, the needs to use peak power units to obtain the balance generation-consumption, usually such units are gas or coal based; even the storage technologies will be mature on medium-term perspective, there are important carbon balancing costs to be considered).

Table 1 Carbon emissions for energy alternatives

		Emissions [g CO_2 eq./kWh]		Potential for improvement
		Min	Max	
1	Coal	751	1095	147–469 g CO_2 eq./kWh by CCS
2	Gas (NGCC plant)	403	513	49 - 220 g CO_2eq./kWh by CCS
3	Hydro	6	147	
4	Solar (CSP)	27	122	*
5	Solar (PV)	8	83	*
6	Onshore W	7.8	16	*
7	Offshore W	12	23	*
8	Nuclear	5.1	6.4	

* Larger value if the complete effects such as the balancing of the system are considered

References

(UNECE, 2021) UNECE, Life Cycle Assessment of Electricity Generation Options, United Nations Geneva, 2021

Fig. 4.6.1 Example of a fiche for an indicator

All the fiches are presented in Annex 2. To be noted the fiches will be updated before each assessment in order to include the most recent and relevant data and information. Therefore, the updating of the fiches is part of the application procedures.

The fiches are simply structured in: (1) definition of the indicators, (2) relevant data/information, (3) references.

The stakeholders may use or not a certain fiche, based on the own knowledge/experience. The fiche is intended only to help a stakeholder to have a look on the most relevant data. The stakeholder may consult the presented references or any other document considered as important for the issue.

The assessment of an indicator/sub-indicator is based on the conversion of the values/attribute of the indicator to a dimensionless scale 0 to 3 (Fig. 4.6.2). The significance of the steps is the following:

0: this score indicates a complete absence or lack of the desired quality or attribute; there is no evidence or indication that the characteristic being assessed is present.

1: minimal or limited presence of the quality or attribute; it is at a very basic or preliminary stage, and there is a significant room for improvement.

2: moderate level of the quality or attribute; there is observable evidence of the characteristic being present, but there is still some room for enhancement or development.

3: high or optimal level of the quality or attribute being assessed; the characteristic is well-developed, fully present, and demonstrates a strong performance.

Fig. 4.6.2 Scale used for the assessment of performance on indicators and sub-indicators

Depending on the composition of the assessment group the scale may be replaced with one more detailed (for example 0 to 5).

For a certain indicator (or sub-indicator) an assessor will read the associated fiche (eventually consult the references or other useful identified documents/sources or simply use his/her own expertise without reading the fiche) trying to understand a technology in the context of the other technologies considered in the analysis.

According with the main considerations presented in [37] the following energy generation technology will be considered in the contextual analysis:

- Hydro,
- Solar PV,
- Solar CSP,
- Onshore wind,

- Offshore wind,
- Nuclear.

Each evaluator, based on personal experience and knowledge or by consulting the elements presented in an indicator fiche, including possible consulting the associated references, will assign a score (0 to 3) taking into account the performance of the targeted technology, In this assignment the evaluator will have a global look on the performances of competing technologies, therefore the maximum of scale (3) will correspond to the maximum performances achieved by one or more energy technologies.

At the moment of the assessment, the evaluators will not have access to the values of the weights in order to not be influenced in a carefully judgement of all the indicators and sub-indicators. They may receive the weights after the finalization of the assessment step.

An Excel application will be used to centralize all the data and calculates the final score, the figure of merit, for the technology.

The method may be used to assess the sustainability performance for one technology or simultaneously for a set of technologies. In ECOSENS, the objective is to assess the nuclear power considering the entire cycle. The assessment will take into consideration the comparison of the sustainability performance for the above-mentioned technologies, all the sub-indicators and indicators.

.7 4.7. Steps of the assessment

In Fig. 4.7.1 the main steps of the methodological development, the preparation and the running of the assessment are presented.

The present deliverable is devoted only to the methodological development, the preparation and assessment steps will be approached separately in the deliverable devoted to the assessment running.

The weighting process is a very sensitive step influencing directly the figure of merit for the envisaged technologies. According with the discussion in the International Stakeholder Workshop, Brussels [34], the beneficiaries (for example policy-makers) should decide on the weights according with the views expressed in the current policies.

Creating an effective assessment group for evaluating the sustainability performance of energy alternatives requires a diverse set of expertise and perspectives. An ideal structure should include: (1) technical experts (for example energy engineers with expertise in various energy technologies, systems, and their operational aspects), (2) environmental scientists (professionals who understand the environmental impact of energy sources, including emissions, waste, and resource use), (3) climate scientists (professionals who understand the contribution of energy sources to greenhouse gas emissions and climate change), (4) economic analysts (experts who can analyze the economic viability and cost-effectiveness of different energy options), (5) social impact analysts (professionals who can evaluate the social implications of energy projects, including effects on communities, health, and equity), (6) energy policy analysts (individuals who are well-versed in energy policies, regulations, and incentives), (7) regulatory compliance specialists (experts who can ensure that energy alternatives adhere to local and international regulations), (8) Life Cycle

Assessment experts (professionals who can conduct life cycle assessments to evaluate the entire environmental impact of energy alternatives, from production to disposal),

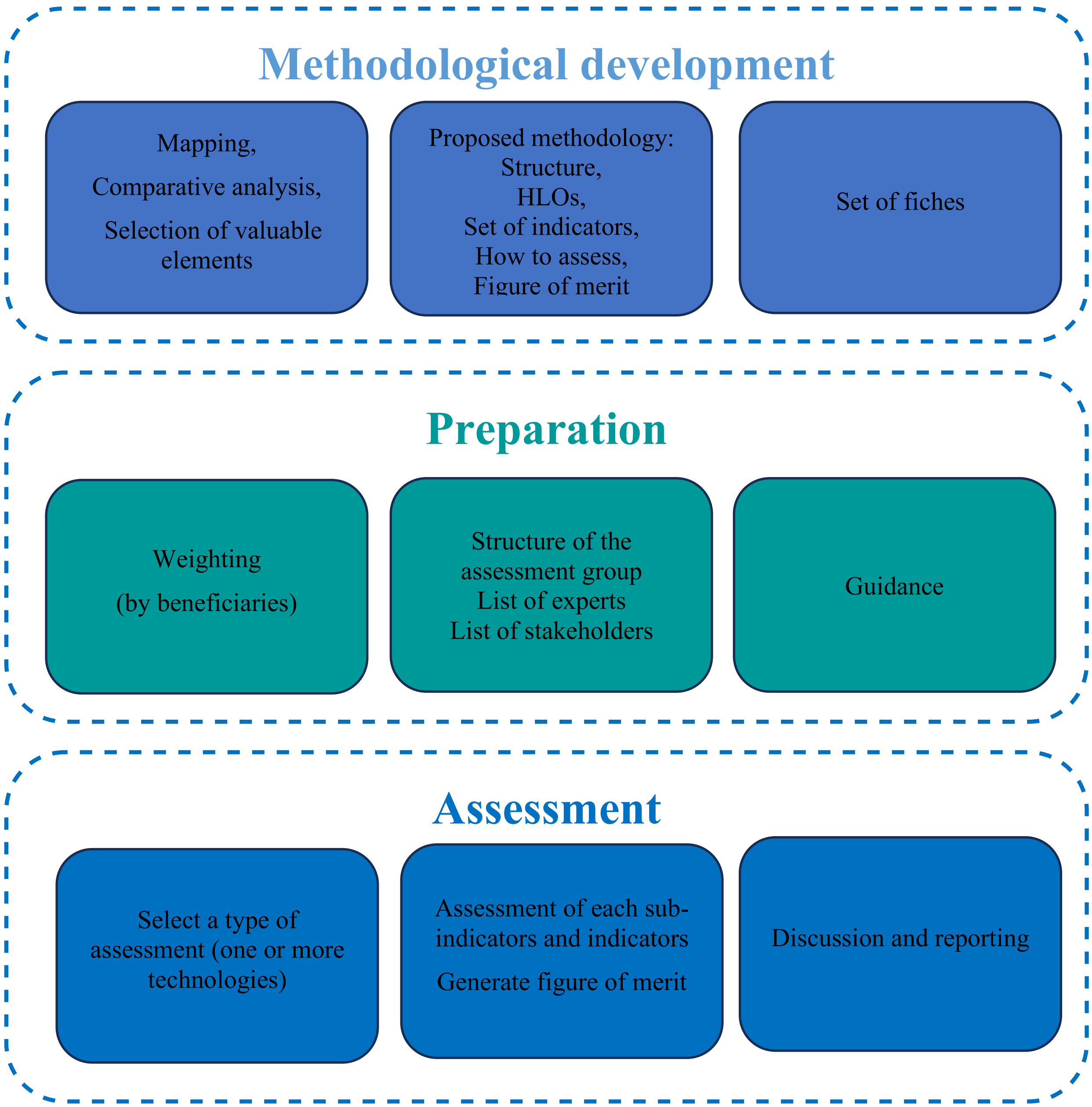


Fig. 4.7.1 Steps of the development and running of ECOSENS methodology

(9) sustainability scientists (professionals with a broad understanding of sustainability principles, capable of bridging the gaps between different disciplines), (10) systems thinkers (individuals who can analyze energy alternatives within the context of broader social, environmental, and economic systems), (11) ethical analysts (experts who can consider the ethical implications of energy choices, including distribution of benefits and burdens), (12) industry representatives

(representatives from relevant industries who can provide insights into practical challenges and opportunities), (13) non-governmental organizations (representatives from environmental and community organizations who can offer critical perspectives), (14) authorities in planning of energy system.

The composition of the assessment group will depend on the specific context, goals, and scope of the sustainability assessment. Such an ideal structure should be simplified in accordance with the planned resources of the ECOSENS project, but for future assessment it should be considered as a starting point.

Guidance structure

Introduction (explain the purpose and scope)

Methodology Overview (overview of the sustainability assessment methodology)

Principles of Sustainability Assessment (Outline the fundamental principles that underpin the assessment, such as the triple bottom line (social, environmental, economic), life cycle thinking, and context specificity)

Framework and Indicators (explain the framework and define specific indicators)

Data Collection and Use (explain how the data from the Fiches are collected and how to use, also the invitation to consult other relevant resources)

Assessment Process (step-by-step guide on how to conduct the sustainability assessment; include guidelines on assigning scores or values to indicators, potentially considering qualitative and quantitative data)

Weighting and Aggregation (communicate on existence of the weights supplied by beneficiaries, explain the process of aggregating indicator scores to produce an overall sustainability performance score)

Interpretation, reporting and communication of the results (communicate the step and how all the participants will access the reports)

Limitations and Considerations (address potential limitations of the assessment methodology, such as data gaps, subjectivity, or cultural biases)

References

Appendices (any additional resources, templates, or tools that can aid in conducting the assessment)

Fig. 4.7.2 Recommended structure for the Guidance document

Creating a comprehensive guidance document for a methodology to assess sustainability performances requires careful consideration of various factors and aspects related to sustainability. A possible structure is presented in Fig. 4.7.2. It should be finalized din the preparatory phase of the assessment.

The selection of the type of assessment is based on the ECOSENS project proposal: entire life cycle assessment of nuclear power, therefore the option of one technology.

5. Consideration on the short-term development of nuclear in Europe

In 2021, around 25% [38] of total electricity in the EU was produced by nuclear reactors, operated in 13 Member state countries (Belgium, Bulgaria, Czechia, Germany, Spain, France, Hungary, the Netherlands, Romania, Slovenia, Slovakia, Finland, and Sweden). The largest share of nuclear electricity in the electricity mix is in case of France (68.9 %), followed by Slovakia (52.4 %) and Belgium (50.6 %) [38]. To be noted, currently, over half of nuclear electricity in EU is produced by France.

Germany is progressively phasing out nuclear reactors, with a drop of 58.7% in nuclear share (2021 vs 2006) with the intention to close all nuclear power production in the next years. Other countries like Austria and Luxembourg have a strong anti-nuclear position. Finally, nuclear is considered controversial in some countries such as Belgium, Portugal, Denmark.

Despite this polarization, nuclear remains a crucial sector for energy production in the EU, offering a powerful contribution for energy security, a large contribution to the decarbonization goal, and creating a strong local supply chain with high-quality jobs. Nuclear electricity in EU today is a major contributor to the decarbonization strategy, currently representing around 40% of low carbon electricity production [39].

The last evolutions at global and EU level, especially the energy crisis and the war in Ukraine, together with increasing climatic pressures, creates more favorable conditions for nuclear development in the short- and medium-term.

The EU policies are focused on growing of the renewable production, energy efficiency measures, electrification of heat, cooling and transportation. In the short-term, the development of such vision is strongly dependent on the grids' balancing capabilities. The grids' interconnection is seen as an important contributor to the balancing, but at national level the diminishing of the dispatchable production (due to the phase out of coal, and reduction of the gas-based energy generation) introduces a compulsory need for storage capacities. Currently, hydro pumping is the single technology offering large capacity storage. However, it is feasible only for some countries with an appropriate landscape and rain regime. Due to the current limits or delays in deployment of electricity storage, the expected high penetration of renewables in energy production is not a realistic option, at least for the short- and medium-term. The implementation of such policy will create more perturbations on the market with significant effect in the energy prices, and highly probable periods of black-out.

In such a context, the development of nuclear has a good opportunity for short-term development. Consequently, it is expected to be more determinant in long-term operation (LTO) projects, and existing nuclear investment is likely to accelerate. This tendency is based on the existing investments and already agreed development planning in the EU (continuation of operation of the existing fleet and support for new build).

A set of EU Member States keeps nuclear in the national energy mix, based on the extension of the lifetime of the current fleet. Other countries intend both LTO and the building of additional capacities. LTO is already decided or in advanced progress for some NPPs such as: Kozloduy (Bulgaria), Dukhovany and Temelin (Czech Republic), Krško (Croatia and Slovenia), Loviisa and

Olkiluoto 1&2 (Finland), Paks (Hungary), Cernavoda U1 (Romania), Bohunice U3&4 (Slovakia), Borssele (Netherlands). In France, a large LTO project (grand carénage project) is in progress.

Some new nuclear power plants are planned to be built in some EU countries. On the other hand, the current policies of several MSs are considering nuclear plants as a feasible option to meet their growing energy needs, especially based on the deployment of small modular reactors (SMRs).

The most relevant cases are presented below [39]:

- Bulgaria: two new reactors at Kozloduy, together with the intention to re-start Belene project, including the consideration of SMR option,
- Czech Republic: Dukhovany U5&6, Temelin U3&4, also exploring SMR implementation,
- Estonia: intention to build first NPP by 2035, possible SMR technology,
- Finland: planning for SMRs both for electricity and cogeneration,
- France: construction up 14 new reactors by 2035, including SMRs,
- Hungary: project Paks II (2 new units to be operational in 2032),
- Netherlands: intention to build two new NPPs by 2035, exploring also SMR option,
- Poland: more units (a total capacity og 6 GWe), the first one to be commissioned in 2033,
- Romania: two new units Cernavoda U3&4 (operational in 2032) and first NPP based on SMR (commissioned by 2028),
- Slovakia: a new unit at Bohunice (operational in 2031),
- Slovenia: considering the building of a second NPP,
- Sweden: planning to replace old nuclear units with new ones, exploring also SMR option.

Also, it should be mentioned the tendency of nuclear development in UK, as a former EU member, currently developing two French-made EPR2 reactors at Hinkley Point C.

The last group of countries (Germany, Italy, Lithuania, and Spain) are clearly oriented towards the decommissioning of their nuclear reactors. A total number of 26 reactors are under decommissioning in Germany, with 3 operating reactors planned to shut down in 2023. Spain is planning to reduce the nuclear installed capacity by 2030. In Belgium, the shutdown of Doel 1&2 old reactors was announced.

Due to the latest evolutions on the energy market and in geopolitics, there is, without doubt, a favorable context for nuclear development in the MSs that consider the nuclear option as a valuable one. On the other hand, the investment in nuclear plants is tempered by some factors such as the magnitude of investment, and the incompressible long period until commissioning and return on investment.

The accelerated development of renewables, especially solar and wind, introduced a large variability in production and difficulty in balancing due to the decrease of dispatchable units such as fossil-fuel based. In a grid with large penetration of intermittent renewable nuclear is obliged to perform load-following. Generally, the nuclear option is to be operated at full power, mainly due to economic reasons (long period until return on investment), but there is also a good experience, such as in France, in operating under a variable regime. However, the limited capacity for load-following of the large reactors (LRs) should be noted. In a LR the variation of power is based on the control rods movement (or dedicated grey rods) or on the modification of the boron concentrations in the core. There are three factors limiting the power variability in a nuclear reactor: (1) reactivity effects, including reactivity reserve, (2) Xe-135 poisoning and induced local oscillations, (3) thermal cycling of materials in the active zone.

French experience shows the following details: (1) daily variations in nuclear power generated are between 5 and 10%, (2) for certain periods the variation may exceed 20%, (3) usual power levels used: 50%, 100%, (4) usual ramps 1-5% / min, (6) some special units in operation (6 hours at low power). France's experience is extremely suggestive regarding the ability of an energy production system with high nuclear penetration to respond to consumption variability.

A Small Modular Reactor (SMR) has larger capabilities for adaptation on the current market needs, including the load-following induced by the high variability of the renewables. According to definition [40], a SMR has an installed power less than 300 MWe (around one-third of the power of a traditional commercial reactor) and it is modular (produced in the factory and transported as a unit to the site). The limitations for load-following described before are relaxed due to the reduced size. Some effect in economics, especially the faster return on investment, may be attractive. As the number of produced units will increase, due to modularization and standardization, a learning effect will create an excellent possibility to reduce the production costs.

The SMR option may diminish the effectivity of the limiting factors, but it is also constrained by the multiplicity effect (reaching a large production of standardized units in factory) and the lack of operational experience.

Strong support from the governments is needed in terms of funding and building of the regulatory context for SMR implementation. Without it, it is improbable that development take place in the existing window of opportunity.

The evolution of the last years confirms the fact that we are, without any doubt, in the middle of a climate crisis. Prevention and mitigation measures are already included in global, regional or country policies. Decarbonization of energy sector is a part of the generalized decarbonized economy the policies are targeting.

At the same time, the world is facing an energy crisis, accentuated by the last evolutions in geopolitics. Nuclear has some opportunities in the short-term, but also some challenges to be solved at the level of the market itself.

In 2017, Euratom published the PINC (nuclear illustrative programme) [41] with projections on nuclear development. According with PINC a decline of the nuclear capacity in EU is expected until 2025 (based on the phase out in some countries), and then "a levelling out to 2050 at 95-105 GWe" [41]. The necessary investment (to 2050) is estimated at 45-50 billion Euro for LTO, 350-450 billion Euro for new plants [41]. According with EU energy strategy [42] the total investment in the energy supply until 2050 is estimate between 3.2-4.2 billion Euro, therefore the investment effort for nuclear represents 18-20% of the total energy investment.

A "nuclear alliance" was set up by 16 European countries to prepare the roadmap to develop an integrated nuclear industry [43]. The objective is to reach a capacity of 150 GWe (2050) much greater than the projection of PINC. Of note, this target was selected to maintain the present share of nuclear electricity (25% in the total EU electricity production). A joint declaration of the alliance

[43] urges the European Commission to promote this objective in the EU's energy strategy. The objective would be reached by implementing LTO programmes and new units (30-45 large reactors, as well as SMRs).

A development in SMR systems seems to be very practicable, and the already existing designs for integral pressurized water-cooled reactor (iPWR) create good opportunities for short- and medium-term implementation. Of note, most of the MSs having intentions to extend their nuclear capacity, are also targeting the implementation of SMR. For example, Romania started the implementation of a SMR power plant (6*77MWe) planning for the operational phase in 2028.

In the mid-term, it is possible to see an acceleration of the existing investments, but also the deployment of SMR plants, depending on the success of the first implementations.

On the other hand, nuclear can contribute to the development of a sustainable hydrogen economy (clean, competitive, and based on water) and it can reduce the emissions due to peaking units based on coal/gas/oil.

Some synergies between nuclear power and iRES development are very practicable: (1) common use of H_2 infrastructure, (2) RDI for optimal use of the wasted heat in nuclear and concentrated solar, (3) digitalization to an optimal use of local grids and resources.

As a general view, the nuclear countries from EU consider that independence and security of supply are the most important priority given the current potential of dependence on the gas imports from countries with political instabilities. It must be noted that three countries (Bulgaria, Hungary, and Slovakia) are very dependent on the nuclear fuel produced in Russia.

6. Conclusions

(C1) A realistic projection of energy consumption on short-, medium- or long-term is dependent on a deep understanding of the economic, social and technological evolution along last decades, together with the identification of some possible turning points generated by identified disruptive changes. A simple extrapolation of the current situation is often unrealistic. For the projection of energy demand at the EU level, on short- and medium-term, a series of assumptions were made, based on the data from literature, as well as elements resulted from the strategic development documents.

Regarding the demographic evolution, the EU population has a slight tendency to decrease without a major impact on energy demand. On the other hand, the trend of increasing life expectancy will lead to an older population with effects on the age profile and occupations. From the point of view of the gross domestic product, based on existing data, an increase of about 70% is possible (2050 compared to 2020). The quality of life will increase progressively, which will involve a greater number of household appliances, as well as an increase in the number of travels.

Climate policies will have an important effect, especially through measures to increase energy efficiency, on the basis of which EU consumption in 2050 will be at least 30% lower than in 2020. On the other hand, the trends of decreasing emissions in the heating & cooling and transport sectors will lead to an increase of the electricity demand, probably a doubling of it (2050 vs 2020). From the point of view of the energy mix, climate policies will stimulate a high penetration of the intermittent renewables.

(C2) The EU Reference Scenarios 2020, developed as a common basis for the understanding of possible evolutions, is useful to understand the possible roles of the energy alternatives on short- medium- and long-term. A progressive decoupling of GDP growth from energy demand growth is predicted, together with a decreasing of GHG emissions by 43.8% (2030 vs 1990). The energy demand will decrease progressively based on the energy efficiency, technology developments, recycling and industry shifting, but the electricity demand will increase substantially due to the decarbonization objectives involving great effort for electrification of H&C and transport. The share of electricity in total final demand will reaches 26% (2030) and 33% (2050) (compared to only 22% in 2015). The consumption of the industry will decrease gradually mainly due to energy efficiency measure and technological development leading to a gradual reduction of the energy intensity. Structural changes in industry are projected by shifting towards high value-added and less energy-intensive products. The energy efficiency will contribute to a substantial decrease of the energy consumption (including the and transport sector) by 2030 with 29.6% (vs 2007) for the primary energy. The energy mix will rely on renewable energy (and nuclear production for some MSs), whereas a major drop in lignite and coal use will occur, together with a major limitation of the gas (and oil) use due to the depletion of domestic production; the overall renewables share will reach 33.2% (2030 total energy mix). The natural gas will continue to play a role acting as bridge fuel, based on low carbon intensity relative to oil & solids, and based on their flexibility characteristics in complementarity with intermittent RES generation. The nuclear power will decline from 107 GW (2020) to 94 GW (2030) and 55 GW (2050) based on decision to phase out in some MSs, and delays in the new buildings. The main factor for nuclear capacity is represented by lifetime extensions. A possible boosting of the investment by SMR deployment is not considered in the RS. The energy storage will be crucial for the balancing of the system, especially for the MS's system with large penetration of intermittent RES. A significant increase of the electric vehicles will occur leading to the decarbonization, but also to the increase of the electricity demand. In the buildings sector, large efforts will be devoted to renovation of the insulation and replacing H&C by energy efficient devices (particularly high-efficiency heat pumps);

(C3) Three methodologies (NESA-IAEA, KIND-IAEA, LCA/LCIA-JRC), aimed to assess the sustainability performances of the nuclear power, were discussed, including by the contribution of some stakeholders gathered in an international workshop. The first methodology was developed to evaluate a national or global nuclear energy system with regard to its long-term sustainability, the second methodology is devoted to the comparison of the sustainability performance of different nuclear technologies or energy scenarios, whereas the third methodology was developed in the context of the EU classification system ("EU Taxonomy") of environmentally sustainable economic activities which is established for the assessment of financial investments. A set of criteria was developed and used to assess the methodologies for the use according with the objectives of ECOSENS project. The assessment performed during the international ECOSENS workshop (Brussels. 2023 March 30) shows the second and third methodology may be adapted to the requests of the project, and a combination of them was proposed as a new methodology.

(C4) A new methodology was proposed by combining advantages of KIND-IAEA (structure and weighting) and LCA/LCIA-JRC (inventory basis). The ECOSENS methodology is structured into three chapters: (1) En-LCA, Environmental life cycle assessment, (2) Ec-LCA, Economic life cycle assessment, and (3) So-LCA, Social life cycle assessment. A set of 42 indicators was defined for the assessment. The selection of the indicators was based on technological neutrality principle. On the hand, the assessment will be achieved involving both experts in the energy and stakeholders representing the society. The high-level objectives defined for the three chapters are: (1) En_LCA, "Contribution to planetary wellbeing", (2) Ec-LCA, "Reliability and resilience of supply", (3) So-LCA, "Social feasibility". A number of 12 indicators are detailed in sub-indicators (42 sub-indicators in total) in order to guide the assessment to take into considerations all the aspects of a certain indicator. For each indicator and sub-indicator, a fiche was developed (the definitions, and the quantitative or qualitative elements extracted from literature) in order to support the assessment, especially for the stakeholders. All the data are referenced to allow the consultation of the original document. The experts or stakeholders having a clear image on the indicators may ignore the content of the fiches. Due to the purpose of the methodology to assess different energy technology) the data presented in the fiches are covering the energy alternatives, at least nuclear and renewables. The proposed content will be updated for any assessment according with the last evolutions and available data.

(C5) The proposed methodology was discussed during ECOSENS international workshop with a general agreement of the participants on the value of the neutral assessment. An exercise to attribute the weights was performed in order to express the opinions of the stakeholders on the possible priorities. Due to the complexity of work only six stakeholders succeed to finalize the exercise. The proposed weights were compared with a reference case defined as an equal weighting for all the indicators. The stakeholders give more importance for some indicators (vs reference case), for example for: "Impact on the local/regional business (partner with other business)" (+115%), "Cost" (+62%), "Cost for system integration" (+62%), "Impact on health improvement" (+56%), "Jobs created" (+50%), "Carbon emissions" (+50%). Other indicators are seen by the stakeholders as having less importance than in the reference case such as: "Contribute to the reduction of inherited burdens (toxic wastes, military stocks)" (-48%), "Societal-level adoption of the technology" (-48%), "Existing investment in RDI to develop the technology" (-48%), "Capacity factor" (-37%), "Applicability for cogeneration" (-37%), "Value of the knowledge generated and maintained for the future" (-35%), "Dependency on government support (funding or incentives, such as tax credits or subsidies)" (-35%).

(C6) The proposed methodology will be applied in the second year of ECOSENS project. The steps to be followed are: the testing of the methodology for a fine tuning, the set-up of the assessment team (experts/specialist) and the stakeholders to be involvement, the assessment itself.

(C7) Some considerations were introduced for the possible evolution of the nuclear power sector on short- and mid-term development of nuclear, based on the current policy framework, needs of the energy market and possible evolutions. Currently in the EU there is a polarization of opinion on the future of nuclear power, a group of MSs being clearly oriented against support of the nuclear. Despite of it, nuclear will remain a crucial contributor for energy security and decarbonization, currently representing around 40% of the free-carbon electricity production. The last evolutions at global and EU level, especially the energy crisis and the war in Ukraine, together with the increasing of the climatic pressures, creates more favorable conditions for nuclear development on short- and medium-term. The fast growing of the intermittent renewable production supported by the energy policies and phase-out of the fossil-fuel based units, will create a big pressure on the balancing of the grid. The increase of the interconnectivity will reduce a part of the pressure, but the most important element, the development of large storage capacity, remains in delay in comparison with the needs. In absence of them, a large penetration of renewable will create more perturbations on the market with significant effect in the energy prices, and highly probable periods of black-out. In such context, the development of nuclear has a good opportunity for short-term development. An impetus on the support both for the long-term operation projects and nuclear already started investment is expected. A development of SMR systems seems to be very practicable, and the already existing designs for integral pressurized water-cooled reactor created good opportunities for short- and medium-term implementation. It is notable, the most of the MSs having intentions to extend their nuclear capacity, are also targeting the implementation of SMR, for example Romania started the implementation of a SMR power plant (6*77MWe) with a planning for the operational phase in 2028. On mid-term, it is possible to have an acceleration of the existing investments, but also the deployment of SMR based plants, depending on the success of the first implementations. On the other hand, nuclear can contribute to the development of a sustainable hydrogen economy (clean, competitive, and based on water) and it can reduce the emissions due to peaking units based on coal/gas/oil. As a general view, the nuclear countries from EU consider the independence and security of supply is the most important priority in condition of the current potential of the gas dependence on the imports from countries with political instabilities.

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8. Annexes

Annex 1, List of Basic Principles for the development of a Innovative Nuclear Systems (INS)

Area	BP
Economics	Nuclear energy products must be competitive against alternative energy sources available in the country. Energy and related products and services from NES shall be affordable and available.
Infrastructure	Country shall be able to adopt, maintain or enlarge an NES for the supply of energy and related products without making an excessive investment in national infrastructure consisting of: (1) Legal and institutional frame work, (2) Industrial and economic infrastructure, (3) Socio-political infrastructure (Public acceptance, Human resources)
Waste management	(W1) **Generation of radioactive waste** shall be kept to the minimum practicable (W2) Radioactive waste shall be managed in such a way as to secure an acceptable level of **protection for human health and the environment**, regardless of the time or place at which impacts may occur (W3) Radioactive waste shall be managed in such a way that it will not impose undue **burdens on future generations**. (W4) Interactions and relationships among all waste generation and management steps shall be accounted for in the design, such that **overall operational and long-term safety is optimized**
Proliferation resistance	Proliferation resistance (PR) intrinsic features and extrinsic measures shall be implemented throughout the full life to help ensure that NES will continue to be an **unattractive means to acquire fissile material for a nuclear weapons program**. Both intrinsic features and extrinsic measures are essential, and neither shall be considered sufficient by itself.
Physical protection	Physical Protection Regime shall be effectively and efficiently implemented for the full lifecycle
Environment	(E1) The expected (best estimate) adverse environmental effects of NES shall be well within the performance envelope of current nuclear energy systems delivering similar energy products. (E2) The NES shall be capable of contributing to the energy needs in the 21st century while making efficient use of non-renewable resources.
Safety	(S1) **(defence in depth)**: Nuclear installations shall incorporate enhanced defence-in-depth as a part of their fundamental safety approach

	(S2) **(inherent safety)**: Installations shall excel in safety and reliability by incorporating into their designs, when appropriate, increased emphasis on inherently safe characteristics and passive systems as a part of their fundamental safety approach. (S3) **(risk of radiation):** Installations shall ensure that the risk from radiation exposures to workers, the public and the environment during construction, commissioning, operation, and decommissioning, are comparable to the risk from other industrial facilities used for similar purposes (S4) **(RD&D)**: The development shall include associated research, development and demonstration work to bring the knowledge of plant characteristics and the capability of analytical methods used for design and safety assessment to at least the same confidence level as for existing plants

Annex 2, Fiches of the indicators and sub-indicators

Fiche 1.1, Carbon emissions

Fiche – summary of data and considerations

Category for the assessment	Environment
Indicator	Carbon emissions
Sub-indicator	-
Date of release	2023 January 10
Responsible partner	RATEN ICN
Contributing organizations	-
Authors	M.Constantin
Version	1.0

The following data are compiled from (UNECE, 2021).

The carbon emission is calculated for entire life cycle of each technology, based on available data for the year 2020.

The indicator is presented in grams of CO_2 released for 1 kWh of electricity produced by the technology.

Nota bene, the data does not consider the carbon produced for the balancing of the energy system (for example, the needs to use peak power units to obtain the balance generation-consumption, usually such units are gas or coal based; even the storage technologies will be mature on medium-term perspective, there are important carbon balancing costs to be considered).

Table 1 Carbon emissions for energy alternatives

		Emissions [g CO_2 eq./kWh]		**Potential for improvement**
		Min	**Max**	
1	Coal	751	1095	147–469 g CO_2 eq./kWh by CCS
2	Gas (NGCC plant)	403	513	49 - 220 g CO_2eq./kWh by CCS
3	Hydro	6	147	
4	Solar (CSP)	27	122	*
5	Solar (PV)	8	83	*
6	Onshore W	7.8	16	*
7	Offshore W	12	23	*
8	Nuclear	5.1	6.4	

* Larger value if the complete effects such as the balancing of the system will be considered

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Fiche 1.2, Land occupation

Fiche – summary of data and considerations

Category of LCA assessment	Environment
Indicator	1.2 Land occupation
Sub-indicator	-
Date of release	2023 September 19
Responsible partner	RATEN ICN
Contributing organizations	-
Authors	M. Constantin
Version	1.0

The following data are compiled from (JRC, 2021), (Dorber, 2018).

The indicator measures the land occupation considering the entire lifecycle of each energy technology. It is expressed in m^2*year/MWh. The land occupation varies significantly based on factors such as the type of technology, capacity, location, and efficiency.

In Table 1 the minimum and maximum values collected in JRC report are presented. The largest value is for coal power followed by solar PV. It should be noted 95% of the land occupation in case of PV is due to the production of the metals for the manufacture of the panels. Land occupation by offshore wind nuclear and gas are negligible.

Table 1 Land occupation for different energy technologies

		Land occupation [m2*year/MWh]	
		Min	**Max**
1	Coal	40.4	59.3
2	Gas (NGCC plant)	1	4
3	Hydro	4	27
5	Solar (PV)	1	5
6	Wind	1	2.5
8	Nuclear	0.5	1

References

(JRC, 2021) JRC, Technical assessment of nuclear energy with respect to the 'do no significant harm' criteria of Regulation (EU) 2020/852 ('Taxonomy Regulation'), 2021

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Fiche 1.3, Energy returned on investment

Fiche – summary of data and considerations

Category of LCA assessment	Environment
Indicator	Energy returned of investment
Sub-indicator	-
Date of release	2023 September 01
Responsible partner	RATEN ICN
Contributing organizations	-
Authors	M. Constantin
Version	1.0

The following data are compiled from (Atlason, 2014), (Hall, 2014), (Hall, 2009), (Freise, 2011), (Sell, 2011) (Dale, 2010), (Kis, 2018), (Weißbach, 2013)

Energy return on investment (EROI) is calculated as the ration between the energy delivered by a particular fuel or technology to the society and the input energy (invested in capturing and delivering this energy to the society). EROI is a measure of the "profit" obtained in terms of energy by investing an amount of energy and obtaining a final usable energy. Sometimes it is referred as energy returned on energy invested.

When EROI is less than 1, the process is a net consumer of energy, therefore it can no longer to be used as a source of energy. A value at least 3 is necessary to consider the viability on the market for a fuel or energy technology. The estimated values for EROI for different energy technologies are presented in Table 1.

Table 1 EROI for different fuels

		EROI	
		Min	**Max**
1	Coal	27 (Hu, 2013)	80 (Hall, 2014)
2	Gas	20 (Freise, 2011)	67 (Sell, 2011)
3	Hydro	10 (Dale, 2010)	105 (Dale, 2010)
4	Solar (CSP)	5.4 (Kis, 2018)	17.9 (Kis, 2018)
5	Solar (PV)	2.7 (Kis, 2018)	7.5 (Kis, 2018)
6	Onshore W	8.1 (Kis, 2018)	34.5 (Kis, 2018)
7	Offshore W	6.9 (Kis, 2018)	19.1 (Kis, 2018)
8	Nuclear	5 (Hall, 2014)	75 (Weißbach, 2013)

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Fiche 1.4.1, Operational water consumption

Fiche – summary of data and considerations

Category of LCA assessment	Environment
Indicator	1.4 Impact on resources
Sub-indicator	1.4.1 Operational water consumption
Date of release	2023 September 15
Responsible partner	RATEN ICN
Contributing organizations	-
Authors	D. Diaconu
Version	1.0

The following data are compiled from available literature sources, listed in the Reference section..

The indicator is presented in m^3 of water consumed for 1 kWh of electricity produced by the technology.

Table 1 Operational water consumption by energy alternative

		Water consumption [m^3/ kWh]		**Potential for improvement**
		Min	**Max**	
1	Coal	2 [1]	2.60 (2011)	Yes, by recirculation of cooling water
2	Gas (NGCC plant)	0.75 [2]	5130.79 [1]	Yes, by recirculation of cooling water
3	Hydro	0.04 [4] 17 (average) [5]	209 [4] 1194 (multipurpose) [5]	
4	Solar (CSP)	3.1 (cooling tower) 3.4 (trough plants) [1]	2.98 (cooling tower) 3.27 (trough plants) [2]	Yes, using molten salts
5	Solar (PV)	0.07 [3]	0.07 [3]	
6	Onshore W	0.003 [7]	0.4 [7]	
7	Offshore W	0.003 [7]	0.4 [7]	
8	Nuclear	2.54 [2]	2.7 [1, 6]	

References

Meldrum, J.; Nettles-Anderson, S.; Heath, G.; MacKnick, J. (March 2013). "Life cycle water use for electricity generation: A review and harmonization of literature estimates". Environmental Research Letters. ***8*** *(1): 015031. Bibcode:2013ERL.....8a5031M. doi:10.1088/1748-9326/8/1/015031.*

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https://www.un-igrac.org/sites/default/files/2021-07/Regional%20Water%20Consumption%20for%20Hydro%20and%20Thermal%20Electricity%20Generation%20in%20the%20US.pdf

T. H. Bakken et al. - Water consumption from hydropower plants – review of published estimates and an assessment of the concept, Hydrol. Earth Syst. Sci., 17, 3983–4000, 2013 www.hydrol-earth-syst-sci.net/17/3983/2013/ doi:10.5194/hess-17-3983-2013 (https://hess.copernicus.org/articles/17/3983/2013/hess-17-3983-2013.pdf)

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Fiche 1.4.2, Abiotic resources depletion

Fiche – summary of data and considerations

Category of LCA assessment	Environment
Indicator	1.4 Impact on resources
Sub-indicator	1.4.2 Abiotic resources depletion
Date of release	2023 September 15
Responsible partner	RATEN ICN
Contributing organizations	-
Authors	D. Diaconu
Version	1.0

The following data are compiled from [1]. Resource refers to all the materials available in our environment technologically accessible, economically feasible and culturally sustainable and may be classified into renewable and non-renewable resources. On the basis of origin, they can be classified as biotic and abiotic. The abiotic resources comprise non-living things (e.g., land, water, air and minerals such as iron, copper, aluminum).

Abiotic resources depletion is defined by the Abiotic Depletion Potential (ADP), a metric used to assess the potential environmental impact of resource depletion in non-living natural resources. It is a way to quantify the depletion of non-renewable resources in a manner that considers the finite nature of these resources and the environmental consequences associated with their extraction and use.

ADP is typically expressed in units such as person-years or kilogram-years and is used to estimate how many years it would take for a particular resource to be depleted completely, taking into account factors like the amount of resource available, the rate of extraction, and the environmental impact associated with that extraction.

The indicator is given in kg·Sb eq per kWh of energy production. It quantifies the potential depletion of various abiotic resources, expressed in kilograms of antimony equivalents, that would result from generating one kilowatt-hour of electricity. It provides a way to evaluate the environmental impact of electricity generation concerning the depletion of non-renewable resources. This unit is part of the broader effort to assess the sustainability and environmental consequences of energy production methods

Table 2 Abiotic resources depletion by energy alternative [1]

		ADP [kg·Sb eq/kWh]
1	Coal	$9.3*10^{-3}$
2	Gas (NGCC plant)	$6*10^{-3}$
3	Hydro	0
4	Solar (CSP)	$3*10^{-3}$
5	Solar (PV)	$3*10^{-3}$
6	Onshore W	$<0.1*10^{-3}$
7	Offshore W	$<0.1*10^{-3}$
8	Nuclear	$<0.1*10^{-3}$

* Larger value if the complete effects such as the balancing of the system are considered

References

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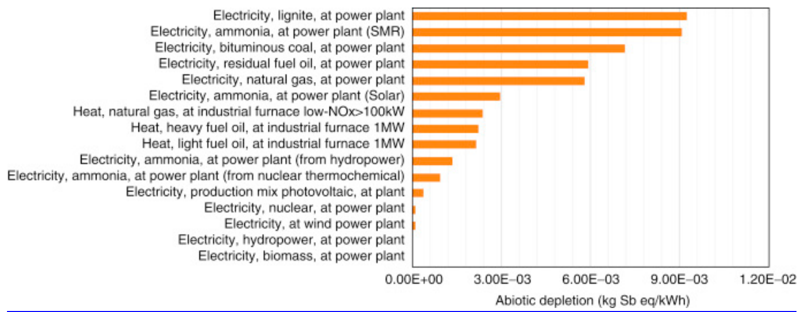

Fiche 1.4.3, Depletion of fossil fuels

Fiche – summary of data and considerations

Category of LCA assessment	Environment
Indicator	1.4 Impact on resources
Sub-indicator	1.4.3 Depletion of fossil fuels
Date of release	2023 September 15
Responsible partner	RATEN ICN
Contributing organizations	-
Authors	D. Diaconu
Version	1.0

The following data are compiled from references listed below.

The depletion of fossil fuels is assessed using Abiotic Depletion Potential (ADP). It is provided for coal, natural and uranium, which was moved uranium from minerals to the fossil energy category (while changing the name of this category to "energy carriers").

The indicator is given in **[kg·Sb/kg]**.

Table 3 1.8.3 Depletion of fossil fuels for each energy alternative

		ADP [kg·Sb/kg]		**Potential for improvement**
		Min	**Max**	
1	Coal	0.00671 [1]		
2	Gas (NGCC plant)	0.0187 [1]		
3	Hydro	NA		
4	Solar (CSP)	NA		
5	Solar (PV)	NA		
6	Onshore W	NA		
7	Offshore W	NA		
8	Nuclear	7.8−03 (average over 46y) [3]	9.4E−03 (average over 5y) [3]	fast reactors

References

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2. *Alwaeli, M.; Mannheim, V. Investigation into the Current State of Nuclear Energy and Nuclear Waste Management—A State-of-the-Art Review. Energies 2022, 15, 4275. https://doi.org/10.3390/en15124275*
3. *van Oers, L., Guinée, J.B. & Heijungs, R. Abiotic resource depletion potentials (ADPs) for elements revisited—updating ultimate reserve estimates and introducing time series for production data. Int J Life Cycle Assess 25, 294–308 (2020).* https://doi.org/10.1007/s11367-019-01683-x

Fiche 1.4.4, Excessive use of resources useful for the life sustaining

Fiche – summary of data and considerations

Category of LCA assessment	Environment
Indicator	1.4 Impact on resources
Sub-indicator	1.4.4 Excessive use of resources useful for the life sustaining
Date of release	2023 September 15
Responsible partner	RATEN ICN
Contributing organizations	-
Authors	D. Diaconu
Version	1.0

Overconsumption means consuming resources that cannot be replenished or that cannot sustain themselves at the rate we are consuming them. Ecosystems are unable to cope with excessive resource extraction, resulting in biodiversity loss and the deterioration of the natural world.

The excessive use of life-sustaining resources was analyzed, qualitatively, from the perspective of the impact on water, air and soil, the three natural resources without which we cannot live.

Table 1 Excessive use of resources useful for the life sustaining

		Excessive use of resources
1	Coal	Coal mining requires extensive land use and can lead to deforestation, habitat destruction, and soil erosion. The combustion of coal releases large amounts of carbon dioxide (CO2) and other air pollutants, contributing to climate change and air pollution.
2	Gas (NGCC plant)	Natural gas extraction involves drilling and hydraulic fracturing (fracking), which can have negative environmental impacts such as water contamination and habitat disruption. However, natural gas combustion produces fewer greenhouse gas emissions compared to coal, making it a relatively cleaner fossil fuel option
3	Hydro	Hydroelectric power generation relies on damming rivers, which can alter aquatic ecosystems and disrupt fish migration patterns. It also requires large amounts of water for reservoirs, affecting local water availability.
4	Solar (CSP)	Solar energy production does not deplete natural resources as it relies on sunlight, which is abundant and renewable. However, the manufacturing process of solar panels requires materials such as silicon, glass, and metals, which have their own environmental impacts. Land use: Larger utility-scale solar facilities can raise concerns about land degradation and habitat loss. Estimates for utility-scale photovoltaic (PV) systems range from 1.4 to 4 ha /MW, while estimates for concentrating solar thermal plants (CSP) are between 1.6 and 6.7 ha/ MW [1].
5	Solar (PV)	

		Water use: Solar PV cells themselves do not use water for generating electricity. However, some water is used in the manufacturing process of solar PV components [1]. CSP plants that use wet-recirculating technology with cooling towers withdraw between 2.3 and 2.5 m3 of water /MWh of electricity produced [1]. Dry-cooling technology can reduce water use at CSP plants by approximately 90% [1]. Hazardous materials: The use of hazardous materials in the manufacturing of solar panels can be a concern. However, advancements in technology have led to the development of safer and more environmentally friendly materials [1].
6	Onshore W	Wind energy production has minimal resource consumption compared to fossil fuel-based power generation. Wind turbines require materials such as steel, concrete, and fiberglass for construction. However, the amount of resources used is relatively small compared to other forms of energy production. Land use: The land use impact varies depending on the site. Wind turbines placed in flat areas typically use more land than those located in hilly areas. However, the turbines themselves and the surrounding infrastructure occupy a small portion of the total area of a wind facility. A survey found that large wind facilities in the United States use between 12 and 57 ha / MW of power output capacity. The remaining land can be used for other productive purposes such as livestock grazing, agriculture, highways, and hiking trails [2].
7	Offshore W	Wind energy production has minimal resource consumption compared to fossil fuel-based power generation. Wind turbines require materials such as steel, concrete, and fiberglass for construction. However, the amount of resources used is relatively small compared to other forms of energy production.
8	Nuclear	Nuclear power generation relies on uranium as fuel. Uranium mining and processing have environmental impacts such as habitat disruption and water contamination. However, nuclear power has a high energy density and produces low greenhouse gas emissions during operation.

References

1. *Environmental Impacts of Solar Power | Union of Concerned Scientists (ucsusa.org)*
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Fiche 1.4.5, Exhausting of rare resources

Fiche – summary of data and considerations

Category of LCA assessment	Environment
Indicator	1.4 Impact on resources
Sub-indicator	1.4.5 Exhausting of rare resources
Date of release	2023 September 15
Responsible partner	RATEN ICN
Contributing organizations	-
Authors	D. Diaconu
Version	1.0

Rare elements, often referred to as rare earth elements (REEs), are a group of 17 chemically similar elements in the periodic table. These elements are crucial components in various advanced technologies.

In solar technology REEs like indium, gallium, and tellurium are used in thin-film solar cells, which are a type of PV solar panel. These elements help improve the efficiency of solar panels and reduce the amount of semiconductor material required. Neodymium is used in the construction of high-performance solar tracking systems, which allow solar panels to follow the sun's movement for maximum energy capture.

In wind technology the wind turbines often use permanent magnet generators, and these generators contain neodymium and dysprosium, which are rare earth elements. These magnets are essential for generating electricity efficiently in wind turbines.

In hydro technology similar to wind turbines, hydroelectric generators may also use rare earth magnets like neodymium to increase their efficiency.

In nuclear technology small amount of REEs like boron and hafnium are used in control rods within nuclear reactors. These control rods help regulate the nuclear fission process by absorbing neutrons and controlling the rate of the nuclear reaction.

While rare earth elements are essential for these technologies, there are concerns regarding their availability and environmental impact. Most rare earth elements are not actually rare in terms of abundance in the Earth's crust, but they are often difficult and environmentally damaging to extract and refine.

Efforts are also being made to diversify the sources of rare earth elements and reduce reliance on a few dominant suppliers to ensure a more stable supply chain for clean energy technologies. Additionally, there is a focus on improving the recycling and sustainable sourcing of these critical materials to minimize their environmental impact.

Table 1 Rare elements used by energy alternative

		Rare elements	Potential for improvement
1	Coal	NA	
2	Gas (NGCC plant)	NA	
3	Hydro	Neodymium	
4	Solar (CSP)		By recycling

5	Solar (PV)	Indium, tellurium, arsenic, gallium, germanium	
6	Onshore W	neodymium and dysprosium	By recycling
7	Offshore W		
8	Nuclear	Small amount of boron and hafnium	

References

(UNECE, 2021) UNECE, Life Cycle Assessment of Electricity Generation Options, United Nations Geneva, 2021

Fiche 1.5, Potential material recyclability

Fiche – summary of data and considerations

Category of LCA assessment	Environment
Indicator	Potential material recyclability
Sub-indicator	-
Date of release	2023 August 17
Responsible partner	RATEN ICN
Contributing organizations	-
Authors	V. Neculae
Version	1.0

The recyclability of the materials is the indicator used to assess the efficiency in the use of natural resources. (Stamford & Azapagic, 2012) have calculated the potential material recyclability ratios for the different technologies. The data present in Table 1 proved that some technologies are more recyclable than others. For instance, 80%–90% of a typical coal, gas or nuclear plant can be recycled, with the limit largely being due to extensive use of concrete. The calculation is based on the inventory of the different materials used in plant construction and their potential recyclability (e.g. most metals are 100% recyclable, concrete is 79.4% recyclable, etc.).

In the case of nuclear power, it was taken into consideration the fact that a proportion of the materials become too activated and cannot be reuse and this proportion, which is less than 5%, was excluded.

Table 1 Potential material recyclability

		Potential material recyclability [%]	
		Min	**Max**
1	Coal	77.7	84.3
2	Gas (NGCC plant)	79.4	89.3
3	Hydro		
4	Solar (CSP)		
5	Solar (PV)	23.8	99.8
6	Wind (Onshore/Offshore)	80.3	99.4
7	Nuclear	73.3	81.2

References

Stamford , L. & Azapagic, A., 2012. Life cycle sustainability assessment of electricity options for the UK. INTERNATIONAL JOURNAL OF ENERGY RESEARCH.

Fiche 1.6.1, Emissions (other than C) - NOx and SO2 emissions

Fiche – summary of data and considerations

Category of LCA assessment	Environment
Indicator	Emissions (other than C)
Sub-indicator	NO_x and SO_2 emissions
Date of release	2023 September 7
Responsible partner	RATEN ICN
Contributing organizations	-
Authors	C. Diaconescu
Version	1.0

The following data are compiled from (UNECE, 2021), (European Commission Joint Research Centre, 2021). (Aitor P. Acero, 2015), (Christian Bauer, Life Cycle Assessment of Fossil and Biomass Power Generation Chains, December 2008) and (PRESS, 2012).

The Sulfur Oxides (SO_2) and Nitrogen Oxides (NO_x) are the major air pollutants, being the most common indicators used in lifecycle assessments in the literature for comparing chemical pollution and its potential impacts on water ecosystems, in relation to air pollution, soil quality and terrestrial ecosystems.

The table 1 shows the NO_x and SO_2 emissions data estimated from the (European Commission Joint Research Centre, 2021) charts.

Table 1 Cumulative lifecycle emissions of NOx and SO2 per unit of energy generated for current electricity supply technologies

		NOx [g/kWh]		SO_2 [g/kWh]	
		min	max	min	max
1	Hard Coal	1.25	4	1	7.5
2	Lignite	0.7	3	1.25	27.5
3	Oil	1.25	4.5	1.25	14
4	Nuclear*	-	-	-	-
5	Natural Gas	0.5	1.5	0.01	6
6	Biomass	0.05	6	0. 05	2.5
7	PV	0.01		0.02	
8	Solar thermal	0.001		0.001	
9	On&Offshore Wind	0.001		0.001	
10	Hydro*	-		-	

* The nuclear energy technology based on current Generation II power plants, along with wind and hydro have relatively very low emissions of these substances compared to fossil fuel technologies.

References

Aitor P. Acero, C. R. (2015). LCIA methods Impact assessment methods in Life Cycle Assessment and their impact categories.

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Fiche 1.6.2, Emissions (other than C) - Ozone depletion potential

Fiche – summary of data and considerations

Category of LCA assessment	Environment
Indicator	Emissions (other than C)
Sub-indicator	Ozone depletion potential
Date of release	2023 July 13
Responsible partner	RATEN ICN
Contributing organizations	-
Authors	C. Diaconescu
Version	1.0

The following data are compiled from (European Commission Joint Research Centre, 2021).

Ozone Depletion Potential (ODP) represents the potential of depletion of the ozone layer due to the emissions of chlorofluorocarbon compounds and chlorinated hydrocarbons. The ODP of the different contributing substances are converted to an equivalent quantity of CFC-11 and the indicator is expressed in units of µg CFC-11 eq/kWh.

The following data are compiled from (Stamford & Azapagic, 2012), (Treyer & Bauer, 2015), (UNECE, 2021)

Table 1 Ozone Depletion Potential for energy alternatives

		Ozone Depletion Potential **[µg CFC-1 eq/kWh]**	
		Min	**Max**
1	Coal	3.2	15.7
2	oil	303	
3	Hydro	3.4	7.8
4	Gas (NGCC plant)	2.8	13.8
5	solar PV	0.91	25.2
6	wind offshore	0.26	2.93
7	wind onshore	0.67	
8	Nuclear	0.46	72.8*
9	CSP	1.3	5.6

*The anomalous upper bound of 73 mg CFC-11 eq./kWh for nuclear power is due to the sensitivity analysis considering the impact of enriching uranium via diffusion: the high impact is due to the use of Freon (CFC-114)6 as coolant in the United States Enrichment Corporation (USEC) diffusion plants. However, this is of little consequence for nuclear power in the UK and is shown here only to illustrate worst-case values for ODP

References

Ch. Poinssot, S. B.-G. (2014). Assessment of the environmental footprint of nuclear energy systems. Comparison between closed and open fuel cycles. Energy - ScienceDirect, 13. doi:http://dx.doi.org/10.1016/j.energy.2014.02.069

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Fiche 1.6.3, Emissions (other than C) - Photochemical oxidant creation potential

Fiche – summary of data and considerations

Category of LCA assessment	Environment
Indicator	Emissions (other than C)
Sub-indicator	Photochemical oxidant creation potential
Date of release	2023 August 18
Responsible partner	RATEN ICN
Contributing organizations	-
Authors	C. Diaconescu
Version	1.0

The following data are compiled from (Stamford & Azapagic, 2012), (Treyer & Bauer, 2015), (UNECE, 2021) and (European Commission Joint Research Centre, 2021).

Photochemical Oxidant Creation Potential (POCP) or photochemical smog is caused by the creation of ozone from volatile organic compounds (VOCs) and nitrogen oxides in the presence of sunlight. Although ozone is critical in the high atmosphere to protect against ultraviolet light, low-level ozone is implicated in impacts as diverse as crop damage and increased incidence of asthma and other respiratory complaints. POCP is usually expressed relative to the oxidant creation potential of ethylene and is expressed using the reference unit, kg C_2H_4 eq/kWh.

Table 1 **Photochemical Oxidant Creation Potential (POCP)** for energy alternatives

		Photochemical oxidant creation potential [mg C_2H_4 eq/kWh]	
		min	max
1	Coal	80	560
2	Gas CCGT	23.1	532
3	Oil	220	950
4	Nuclear	4.5	35.4
5	Wind offshore	3.47	222
6	Solar PV	33.9	253
7	Solar thermal	10	30
8	Hydro		10
9	Geothermal	20	40

References

Ch. Poinssot, S. B.-G. (2014). Assessment of the environmental footprint of nuclear energy systems. Comparison between closed and open fuel cycles. Energy - ScienceDirect, 13. doi:http://dx.doi.org/10.1016/j.energy.2014.02.069

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Fiche 1.6.4, Emissions (other than C) - Cumulative lifecycle emissions of NMVOC and PM2.5

Fiche – summary of data and considerations

Category of LCA assessment	Environment
Indicator	Emissions (other than C)
Sub-indicator	Cumulative lifecycle emissions of NMVOC and PM2.5
Date of release	2023 September 7
Responsible partner	RATEN ICN
Contributing organizations	-
Authors	C. Diaconescu
Version	1.0

The following data are compiled from (UNECE, 2021), (European Commission Joint Research Centre, 2021). (Aitor P. Acero, 2015), (Christian Bauer, Life Cycle Assessment of Fossil and Biomass Power Generation Chains, December 2008) and (PRESS, 2012).

Particulate Matter is a complex mixture of extremely small particles. Particle pollution can be made up of a number of components, including acids (such as nitrates and sulphates), organic chemicals, metals, and soil or dust particles. A multitude of health problems, especially of the respiratory tract, are linked to particle pollution. PM2.5 are particulate matter with a diameter of less than 2.5 micrometers.

Non-methane volatile organic compounds (NMVOC) are a set of organic compounds which may differ widely in their chemical composition, there are photochemically reactive in the atmosphere.

Table 1 shows the cumulative lifecycle emissions of NMVOC and PM2.5 per unit of energy generated for current electricity supply technologies estimated from (PRESS, 2012).

Table 1 Cumulative lifecycle emissions per unit of energy generated of NMVOC and PM2.5 for current electricity supply technologies

		PM2.5 [g/kWh]		NMVOC [g/kWh]	
		min	max	min	max
1	Hard Coal	0.02	1.87	0.03	0.1
2	Lignite	0.03	2.3	0.01	0.03
3	Oil	0.03	1.175	0.25	0.52
4	Nuclear	0.01	0.01	0.001	0.001
5	Natural Gas CCS*	0.0087	0.053	0.05	0.65
	Biomass	0.30	0.52	-	-
6	Wind offshore	0.01		0.01	
7	PV	0.01		0.01	0.12
8	Solar thermal	0.01		0.01	0.12
10	On&Offshore Wind	0.01		0.01	

* (Christian Bauer, Life Cycle Assessment of Fossil and Biomass Power Generation Chains, December 2008)

Nuclear energy has very low PM (particulate matter) and NMVOC (non-methane volatile organic compounds) emissions the values are comparable to the emissions of solar PV and wind.

References

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Fiche 1.7.1, Impact on life and ecosystems (under normal operation)- Human toxicity potential

Fiche – summary of data and considerations

Category of LCA assessment	Environment
Indicator	Impact on the life and ecosystems (normal operation)
Sub-indicator	Human toxicity potential
Date of release	2023 July 19
Responsible partner	RATEN ICN
Contributing organizations	-
Authors	V. Neculae
Version	1.0

Human toxicity potential (HTP) is a measure of the effect of toxic substances on human health considering all exposure routes for all chemicals for an infinite time frame. Important contributing substances include heavy metals as well as particulate matter, SO_x and NO_x emissions, volatile organic compounds (VOC) and chlorinated organic compounds among others.

The indicator used to categorise human toxicity potential is measured in 1,4-dichlorobenzene equivalent/kWh.

The following data from Table 1 Human toxicity potential for energy alternativesTable 1 are compiled from (European Commission Joint Research Centre, 2021) and are based on several recent studies. Note that ionizing radiation is not included in the human toxicity potential data presented.

Table 1 Human toxicity potential for energy alternatives

		HTP [g 1.4-DCB eq./kWh]		**Potential for improvement**
		Min	**Max**	
1	Coal	58	458	73-130 g 1.4-DCB eq./kWh by CCS (Santoyo-Castelazo, 2011)
2	Gas (NGCC plant)	2	27.6	23.7 g 1.4-DCB eq./kWh by future NGCC plants*
3	Hydro	1.63	4	
4	Solar (CSP)	6.98	90	
5	Solar (PV)	35.7	115	HTP can be reduced by recycling (the sensitivity analysis shows that recycling a mono-Si PV panel reduces its HTP by 54%.) (Stamford & Azapagic, 2012)
6	Wind (Onshore/Offshore)	31.5	225	HTP decrease depending on the end-of-life recycling rate (Wang, et al., 2019) (Stamford & Azapagic, 2012)
7	Nuclear	1.23	135	HTP decreased when shifting from the OTC (once-through fuel cycle) to the TTC (twice-through cycle) (Poinssot, et al., 2014)**

* Gas Plants equipped with CCS perform slightly worse than comparable future NGCC plants (Treyer & Bauer, 2015)

**Plutonium recycling in MOX fuel will reduce the need for fresh uranium from mining operations, thereby reducing the related contribution to the HTP (European Commission Joint Research Centre, 2021).

In (UNECE, 2021) the human toxicity is assessed using two indicators: non-carcinogenic effects, and carcinogenic effects. The main contributing substance to non-carcinogenic potential impact is arsenic (in ionic form), emitted to surface and groundwater, and the main substance contributing to carcinogenic potential impact is hexavalent chromium (chromium VI), emitted to water.

The characterization factor for human toxicity impacts (human toxicity potential) is expressed in comparative toxic units (CTUh), the estimated increase in morbidity in the total human population, per unit mass of a chemical emitted, assuming equal weighting between cancer and non-cancer due to a lack of more precise insights into this issue.

Unit: [CTUh per kg emitted] = [disease cases per kg emitted].

Table 2 Human toxicity potential (non-carcinogenic/carcinogenic)

		Human toxicity potential, *non-carcinogenic* [CTUh/TWh]		**Human toxicity potential, *carcinogenic* [CTUh/TWh]**	
		Min	**Max**	**Min**	**Max**
1	Coal	43	166	4.1	10
2	Gas (NGCC plant)	11	27	1.2	5.3
3	Hydro	0.8	22	0.2	2.6
4	Solar (CSP)	1.6	13	1.4	19
5	Solar (PV)	2.4	33	0.8	10
6	Onshore W	1.9	3.9	4.1	8.4
7	Offshore W	5.4	12.8	4.9	11
8	Nuclear	5.2	5.4	0.51	0.52

References

European Commission Joint Research Centre, 2021. Technical assessment of nuclear energy with respect to the 'do no significant harm' criteria of Regulation (EU) 2020/852 ('Taxonomy Regulation'), s.l.: Petten.

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Fiche 1.7.2, Impact on life and ecosystems (under normal operation)-Human health/mortality impact

Fiche – summary of data and considerations

Category of LCA assessment	Environment
Indicator	Impact on the life and ecosystems (normal operation)
Sub-indicator	Human health/mortality impact
Date of release	2023 September 12
Responsible partner	RATEN ICN
Contributing organizations	-
Authors	V. Neculae
Version	1.0

The human health impact for selected energy technologies was calculated by (Hirschberg, et al., 2016) using two approaches: the first is based on lifecycle impact analysis (LCIA) and uses the ReCiPe method and the second uses an Impact Pathway Approach (IPA) based on methods developed in the European Union-funded ExternE research project (European Commission, 2005).

It should be mentioned that the results of IPA and LCIA are not directly comparable. With LCIA results, the approaches to estimation vary greatly depending on the particular LCIA-method chosen as well as to a greater extent on subjective elements related to the various social perspectives while not all owing simulation of site-specific effects (as opposed to IPA).

The indicator resulting from the analysis using the ReCiPe method is measured in units of DALYs (*Disability Adjusted Life Years* which means years of life lost plus years lived with a disability) per unit of electricity generated. The mortality impacts of normal operation assessed using IPA are quantified in terms of Years of Life Lost (YOLLs) per unit of electricity generated.

The health impact estimators have different scopes, i.e. YOLLs derived using IPA area subset of DALYs generated using LCIA. The estimates based on LCIA cover not only health impacts of major pollutants but also the highly uncertain ones caused by the climate change; the latter are not included in IPA-estimates.

Different effects were taken into account in the assessment of the impacts on human health from normal operation for electricity production. Climate change is one of the effects included and the results are shown individually in Table 1, in column "*LCA-based total human health, with climate change [mDALY/kWh]*". The other effects included are human toxicity, ionizing radiation, photochemical oxidant formation, and particulate matter formation (without climate change) and the results are presented together in Table 1 in column "*LCA-based total human health, without climate change [mDALY/kWh]*".

Three different social perspectives—hierarchist (H), egalitarian (E), and individualist (I)—were used in the LCA calculations. The hierarchist perspective could be seen as a kind of well-balanced alternative between the other two, more extreme perspectives. For this reason, the results shown in the table only apply to the Hierarchist perspective.

Depending on the chosen perspective, the absolute results differ significantly, but the ranking of the technologies is mostly unaffected—with the exception of gas, whose impact is comparable to that of nuclear and renewable energy under the Egalitarian perspective but significantly greater under the other perspectives. The Egalitarian perspective is less dominated by impacts due to climate change.

Additionally, mortality data for the same technologies calculated by (Hirschberg, et al., 2016) using IPA are shown in the column "*IPA-based [mYOLL/GWh]*" of Table 1.

Table 1 Human health impact

		Human health impact			
		LCA-based total human health, with climate change [mDALY/kWh]	**LCA-based total human health, without climate change [mDALY/kWh]**	**IPA-based [mYOLL/ GWh]**	**Total health impacts from radiation [DALY/kWh]**
1	Coal	1449	319	59	$2.15 \cdot 10^{-10}$ □ $2.21 \cdot 10^{-9}$
2	Gas (NGCC plant)	598	30	-	$1.16 \cdot 10^{-11}$ □ $2.53 \cdot 10^{-9}$
3	Hydro	10	6	2	-
4	Solar (CSP)	49	18	-	-
5	Solar (PV)	-	-	19	$1.13 \cdot 10^{-9}$ □ $2.88 \cdot 10^{-9}$
6	Wind (Onshore/Offshore)	42	30	6	$1.86 \cdot 10^{-11}$ □ $6.66 \cdot 10^{-11}$
7	Nuclear	56	49	5	$2.03 \cdot 10^{-8}$ □ $3.19 \cdot 10^{-8}$

Referring to total human health impacts from radiation and according with (Stamford & Azapagic, 2012) all technologies have health impacts because of the background processes in their respective life cycles (see values from column "*Total health impacts from radiation [DALY/kWh*]" of Table 1). This is typically as a result of emissions of radon and thorium during mining and milling processes. However, the impact of nuclear power is an order of magnitude greater than that of any other option with a value of 20.3 disability-adjusted life years (DALYs) per TWh. Approximately 90% of this impact is caused by emissions to air of radon-222 from uranium mine tailings over a period of thousands of years, with the remainder being emissions of isotopes like carbon-14 during power plant operation (although this will vary with reactor type).

References

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Fiche 1.7.3, Impact on life and ecosystems (under normal operation)- Ecotoxicity

Fiche – summary of data and considerations

Category of LCA assessment	Environment
Indicator	Impact on the life and ecosystems (normal operation)
Sub-indicator	Ecotoxicity
Date of release	2023 Aug 10
Responsible partner	RATEN ICN
Contributing organizations	-
Authors	V. Neculae
Version	1.0

The following data are compiled from (European Commission Joint Research Centre, 2021) and are based on several recent studies.

Biodiversity is an important factor in the well-being of ecosystems. Biodiversity loss is seen as a long-term problem that negatively affects the natural functions of the ecosystem, which in many contexts (e.g. agriculture, tourism, etc.) represent valuable and even essential assets of human society. Ecotoxicity is one of the indicators that characterizes the potential for damage to biodiversity.

Environmental toxicity can be assessed by analyzing each impact category for freshwater, marine and terrestrial. The freshwater ecotoxicity and marine ecotoxicity were assessed in Annex …Fiche for Freshwater ecotoxicity and Annex..., Fiche for Marine ecotoxicity

Terrestrial ecotoxicity potential (TETP) refers to the impact on non-human living organisms of terrestrial ecosystems resulting from lifecycle emissions of toxic substances to air, water and soil.

Similar to the aquatic ecotoxicity potential, the indicator used to classify the terrestrial ecotoxicity potential is measured in 1,4-dichlorobenzene equivalent mass per unit of electricity generated.

The data from Table 1 are compiled from (Stamford & Azapagic, 2012) and (Treyer & Bauer, 2015) and were calculated using two different methodologies (CML 2001 methodology and ReCiPe methodology).

Table 1 Terrestrial ecotoxicity potential

		TETP [g 1.4-DCB eq./kWh]		**Potential for improvement**
		Min	**Max**	
1	Coal	0.610	1.780	
2	Gas (NGCC plant)	0.025	0.530	
3	Hydro*	0.00522	0.0089	
4	Solar (CSP)	0.001		
5	Solar (PV)	0.087	1.33	decreasing TETP by 37% by recycling the metals
6	Wind (Onshore/Offshore)	0.10	1.93	decreasing TETP by 28% by recycling the metals
7	Nuclear	0.03	0.88	

* Data from (Yuguda, et al., 2019)

Data from (Stamford & Azapagic, 2012) show that, under the most favorable assumptions, coal is comparable to nuclear, offshore wind and solar power. The latter two have the drawback of having relatively high metal requirements. Over 95% of the impact is due to emissions of heavy metals such as chromium, mercury and arsenic in the steel and copper production chains. The same process contributes significantly to his TETP from nuclear energy, but to a much lesser extent. More than half of the impact is due to the release of heavy metals into the atmosphere from uranium plant tailings.

The data from (Treyer & Bauer, 2015) were calculated using the ReCiPe methodology and show significantly lower values. The ranking is also different, with nuclear energy having the lowest impact, followed by wind, gas, solar and oil.

Ecotoxicity potential was also assessed in the NEEDS project (Simons, et al., 2011). The indicator quantifies the loss of species (flora & fauna) due to the release of ecologically toxic emissions to air, water and soil.

The indicator is expressed in terms of Potentially Disappeared Fraction of species on 1 m^2 of earth surface during one year ($PDFm^2$ a) per unit of electricity produced and the values are presented in Table 2.

The concept of PDF is defined as the proportion of locally existing species that become extinct (or "disappear") due to exposure due to an environmental pressure (land use, ecotoxicity, climate change, eutrophication). The ‘disappearance’ of species quantified by PDF is considered reversible once the pressure has ceased (Rossberg, 2022).

For example, 10 $PDFm^2$ a, can be interpreted as:

- 10 m^2 has lost all its species during a year
- 100 m^2 has lost 10% of its species during a year
- 10 m^2 has lost 10% of its species during 10 years.

Table 2 Ecotoxicity potential

	Ecotoxicity [$PDFm^2$ a/kWh]	
	Min	**Max**
Coal	7.67E-04	3.03E-03
Gas (NGCC plant)	3.09E-04	6.34E-04
Hydro		
Solar (CSP)	1.16E-03	1.21E-03
Solar (PV)	8.02E-04	2.40E-03
Wind (Onshore/Offshore)	8.78E-04	1.00E-03
Nuclear	2.83E-04	5.45E-04

References

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Fiche 1.7.4, Impact on life and ecosystems (under normal operation)- Acidification and eutrophication potential

Fiche – summary of data and considerations

Category of LCA assessment	Environment
Indicator	Impact on the life and ecosystems (normal operation)
Sub-indicator	Acidification and Eutrophication potential
Date of release	2023 May 30
Responsible partner	RATEN ICN
Contributing organizations	-
Authors	C. Diaconescu
Version	1.0

The following data are compiled from (European Commission Joint Research Centre, 2021).

Acidification potential refers to the compounds that are precursors to acid rain. These include sulphur dioxide (SO_2), nitrogen oxides (NO_x), nitrogen monoxide (NO), nitrogen dioxide (N_2O), and other various substances. Acidification potential is usually characterized by SO_2^-equivalence (g SO_2-eq/kWh).

Eutrophication is the gradual increase in the concentration of phosphorus, nitrogen, and other minerals and plant nutrients in aquatic ecosystems resulting in over-enrichment that can give rise to excessive growth of algae and depletion of oxygen that supports healthy underwater life.

The indicator for eutrophication potential is expressed in grams phosphate equivalent per unit of electricity generated (g PO_4^{3-} -eq/kWh). Some methodologies calculate freshwater and marine eutrophication potentials separately. As phosphorous is the key limiting nutrient for freshwater eutrophication, its units are g P-eq/kWh, whereas for marine water, nitrogen is most often the key limiting nutrient, so that the units of marine eutrophication are g N-eq/kWh.

The following data are compiled from (Stamford & Azapagic, 2012), (Santoyo-Castelazo, 2011), (Treyer & Bauer, 2015) (Wang, et al., 2019), (UNECE, 2021).

Table 1 Eutrophication potential for energy alternatives

		Emissions [g PO_4^{3-} eq./kWh]		**Emissions_ Freshwater eutrophication [g P eq. / kWh]**		**Emissions Marine Eutrophication][g N eq. / kWh]**	**Potential for improvement**
		Min	**Max**	**Min**	**Max**		
1	Coal	0.141	2.24	0.151	1.6		
2	Gas (NGCC plant)	0.060	0.071	0.00502	0.035	0.012	0.0106 by future NGCC
3	Hydro		0.004	0.00076	0.013	0.0522	
4	Solar (CSP)			0.0051	0.041	0.044	
5	Solar (PV)	0.038	0.3	0.0052	0.096	0.025	
6	Onshore W			0.0041	0.0086		
7	Offshore W	0.02	0.094	0.0061	0.011	0.0252	
8	Nuclear	0.0052	0.022	0.00257	0.0071	0.0522	

The data from table 2 are compiled from (Ch. Poinssot, 2014) (Treyer & Bauer, 2015) (Santoyo-Castelazo, 2011)**.**

Table 2 Acidification potential for energy alternatives

		Emissions [g so_{2-} eq./kWh]		**Potential for improvement**
		Min	**Max**	
1	Coal	0.7	11	0.8–1.5 g **so_{2-}** eq./kWh by CCS (Santoyo-Castelazo, 2011)
2	Gas (NGCC plant)	0.122	1.37	1.2 g so_{2-} eq./kWh by NGCC future (Treyer & Bauer, 2015)
3	Hydro		0.0162	(Wang, et al., 2019)
4	Solar (CSP)		0.076	(Treyer & Bauer, 2015)
5	Solar (PV)	0.3	0.6	
7	Offshore Wind	0.0335	0.365	
8	Nuclear	0.039	0.115	0.034 g so_{2-} eq./kWh by French TTC (Ch. Poinssot, 2014)

References

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Treyer, K., & Bauer, C. (2015). The environmental footprint o fUAE's electricity sector: Combining life cycle assessment and scenario modeling. Renewable and Sustainable Energy Reviews. doi:http://dx.doi.org/10.1016/j.rser.2015.04.016i

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Fiche 1.7.5, Impact on life and ecosystems (under normal operation)- Freshwater ecotoxicity

Fiche – summary of data and considerations

Category of LCA assessment	Environment
Indicator	Impact on the life and ecosystems (normal operation)
Sub-indicator	Freshwater ecotoxicity
Date of release	2023 July 19
Responsible partner	RATEN ICN
Contributing organizations	-
Authors	V. Neculae
Version	1.0

The following data are compiled from (European Commission Joint Research Centre, 2021) and are based on several recent studies.

Freshwater aquatic ecotoxicity potential (FAETP), in general terms, refers to the impact on fresh water ecosystems, as a result of emissions of toxic substances to air, water and soil. The toxic effect is causing biodiversity loss and/or species extinction.

The indicator is expressed as grams 1,4-dichlorobenzene equivalents/kWh (g 1,4-DCB-eq/kWh).

Table 1 Freshwater ecotoxicity

		FAETP [g 1.4-DCB eq./kWh]	
		Min	**Max**
1	Coal	5.27	399.0
2	Gas (NGCC plant)	1.72	7.73
3	Hydro*	0.6	0.8
4	Solar (CSP)	0.23	
5	Solar (PV)	7.32	25.2
6	Wind (Onshore/Offshore)	8.68	56.3
7	Nuclear	3.83	25.8

* Data are compiled from (Santoyo-Castelazo, 2011).

References

European Commission Joint Research Centre, 2021. Technical assessment of nuclear energy with respect to the 'do no significant harm' criteria of Regulation (EU) 2020/852 ('Taxonomy Regulation'), s.l.: Petten.

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Fiche 1.7.6, Impact on life and ecosystems (under normal operation)- Marine ecotoxicity

Fiche – summary of data and considerations

Category of LCA assessment	Environment
Indicator	Impact on the life and ecosystems (normal operation)
Sub-indicator	Marine ecotoxicity
Date of release	2023 July 19
Responsible partner	RATEN ICN
Contributing organizations	-
Authors	V. Neculae
Version	1.0

The following data are compiled from (European Commission Joint Research Centre, 2021) , (Santoyo-Castelazo, 2011), (Treyer & Bauer, 2015), (Stamford & Azapagic, 2012) and (Atilgan & Azapagic, 2015).

Marine aquatic ecotoxicity potential (MAETP) refers to impacts of toxic substances on marine ecosystems leading to damages on ecosystem quality. The toxic effect is causing biodiversity loss and/or species extinction.

The indicator is expressed as kilograms 1,4-dichlorobenzene equivalents/kWh (kg 1,4-DCB-eq/kWh).

Table 1 Marine ecotoxicity

		Marine ecotoxicity [kg 1.4-DCB eq./kWh]	
		Min	**Max**
1	Coal	$6.22 \cdot 10^{-4}$	2240
2	Gas (NGCC plant)	$5.3 \cdot 10^{-4}$	30.7
3	Hydro	1.0	3.5
4	Solar (CSP)	$2.32 \cdot 10^{-4}$	
5	Solar (PV)	$6.72 \cdot 10^{-4}$	122
6	Wind (Onshore/Offshore)	$4.87 \cdot 10^{-4}$	46.4
7	Nuclear	6.68	56.1

The maximum values for marine toxicity are from (Stamford & Azapagic, 2012) and have been assessed using CML methodology. The minimum values are from (Treyer & Bauer, 2015) and have been obtained using ReCiPe methodology. The CML methodology produces significantly larger values for the marine ecotoxicity than the ReCiPe methodology.

References

Atilgan, B. & Azapagic, A., 2015. Assessing the Environmental Sustainability of Electricity Generation in Turkey on a Life Cycle Basis. Energies.

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Fiche 1.7.7, Impact on life and ecosystems (under normal operation)- Biodiversity of the used land

Fiche – summary of data and considerations

Category of LCA assessment	Environment
Indicator	Impact on the life and ecosystems (normal operation)
Sub-indicator	Biodiversity of the used land
Date of release	2023 August 21
Responsible partner	RATEN ICN
Contributing organizations	-
Authors	V. Neculae
Version	1.1

The following data are compiled from (Schenler, et al., 2008) and (Dober, et al., 2020).

Human land use, i.e. changing the natural state of land by human activities, is one of the potential reasons for loss of biodiversity, meaning loss of species.

The indicator quantifies the loss of species (flora & fauna) due to land use. It is given in terms of "potentially disappeared fraction" of species on one m^2 of earth surface during one year (PDFm^2a) per unit of electricity produced.

The concept of PDF is defined as the proportion of locally existing species that become extinct (or "disappear") due to exposure due to an environmental pressure (land use, ecotoxicity, climate change, eutrophication). The 'disappearance' of species quantified by PDF is considered reversible once the pressure has ceased (Rossberg, 2022).

For example, 10 PDFm^2 a, can be interpreted as:

- 10 m^2 has lost all its species during a year
- 100 m^2 has lost 10% of its species during a year
- 10 m^2 has lost 10% of its species during 10 years.
-

Table 1 Biodiversity of the used land

		Biodiversity [PDFm^2a /kWh]	
		Min	**Max**
1	Coal	$7.09 \cdot 10^{-4}$	$6.72 \cdot 10^{-3}$
2	Gas (NGCC plant)	$1.20 \cdot 10^{-3}$	$3.21 \cdot 10^{-3}$
3	Hydro*	$6.7 \cdot 10^{-5}$	$2.7 \cdot 10^{-4}$
4	Solar (CSP)	$4.98 \cdot 10^{-3}$	$5.22 \cdot 10^{-3}$
5	Solar (PV)	$2.19 \cdot 10^{-4}$	$4.69 \cdot 10^{-3}$
6	Wind (Onshore/Offshore)	$1.57 \cdot 10^{-4}$	$1.79 \cdot 10^{-4}$
7	Nuclear	$5.62 \cdot 10^{-5}$	$2.26 \cdot 10^{-4}$

*Data from (Dober, et al., 2020)

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Fiche 1.8.1, Impact of generated wastes - Chemical (generated) waste volumes

Fiche – summary of data and considerations

Category of LCA assessment	Environment
Indicator	1.8 Impact of generated wastes
Sub-indicator	1.8.1 Chemical (generated) waste volumes
Date of release	2023 September 15
Responsible partner	RATEN ICN
Contributing organizations	-
Authors	D. Diaconu
Version	1.0

The following data are compiled from the references below.

The chemical (generated) waste volumes are calculated for plant operation. For nuclear energy, the waste volume includes the waste generated from fuel fabrication and reprocessing.

The indicator is presented in g of chemical waste released for 1 kWh of electricity produced by the technology.

Table 1 Chemical waste volumes generated by energy alternative

		Waste volume [g/ kWh]	
		Min	**Max**
1	Coal* (ref 1, 2, 13)	155 (without CO2, only operation)	1620 (including CO2, only operation)
2	Gas* (NGCC plant) (ref 12)	0.13 (only operation)	27.7 (only operation)
3	Hydro *	0	0
4	Solar ** (CSP) (ref 5, 6, 7)	0.3	0.6
5	Solar ** (PV) (ref3, 4)	1.16	2.05
6	Onshore W ** (ref 10)	0.83	1.45
7	Offshore W** (ref 8, 9)	0.81	1.52
8	Nuclear*** (ref 11)	0.72	0.72

* waste from operation
** waste from decommissioning
*** non-radioactive waste arising from UF6 Conversion Plants, Isotopic Enrichment, Fuel Reprocessing Plant

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Fiche 1.8.2, Impact of generated wastes - Radioactive wastes (generated)

Fiche – summary of data and considerations

Category of LCA assessment	Environment
Indicator	1.8 Impact of generated wastes
Sub-indicator	1.8.2 Radioactive wastes (generated)
Date of release	2023 September 15
Responsible partner	RATEN ICN
Contributing organizations	-
Authors	D. Diaconu
Version	1.0

The following data is compiled from the information and data published in the references listed below.

The radioactive waste volumes are calculated considering the entire life cycle of each technology, based on available data.

The indicator is presented in g of radioactive waste released for 1 kWh of electricity produced by the technology.

Table 2 Radioactive waste volumes generated by energy alternative

		Waste volume [g/ kWh]		**Potential for improvement**
		Min	**Max**	
1	Coal*	6.48	6.48	No
2	Gas (NGCC plant)	no		
3	Hydro	no		
4	Solar (CSP)	no		
5	Solar (PV)	no		
6	Onshore W	no		
7	Offshore W	no		
8	Nuclear (ref 1, 2)	0.01** 0.36***	0.025* 0.36**	Yes, with the implementation of advanced reactors

* fly ash containing U and Th, released in the environment.
** Waste produced at Reactor Site (Low-Level), Produced at Reprocessing Plant (High-Level Vitrified), Cladding Hulls, Low-Level Solids, at Fuel Fabrication Plant Pu Contaminated (ref 1)
***waste from decommissioning

References

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Fiche 1.8.3, Impact of generated wastes - Maturity of the approach (experience and effectivity in waste management)

Fiche – summary of data and considerations

Category of LCA assessment	Environment
Indicator	1.8 Impact of generated wastes
Sub-indicator	1.8.3 Maturity of the approach (experience and effectivity in waste management)
Date of release	2023 September 15
Responsible partner	RATEN ICN
Contributing organizations	-
Authors	D. Diaconu
Version	1.0

The following data is compiled from the information and data published in the references listed below.

The maturity of the waste management approach has been estimated based the TRL scale, considering the experience and effectivity of this process as applied at present in each energy alternative, according to the literature search. Maturity assessment refers to the entire whole life cycle of the energy alternative.

Table 3 1.8.3 Maturity of the approach (experience and effectivity in waste management) for each energy alternative

		Maturity (on TRL scale)		**Potential for improvement**
		Min	**Max**	
1	Coal (ref 1)	9	9	Management approach established, not always effectively implemented
2	Gas (NGCC plant) (ref 1)	9	9	
3	Hydro (ref 1)	9	9	
4	Solar* (CSP) (ref 2)	1	5	yes
5	Solar* (PV) (ref 2)	1	5	yes
6	Onshore W* (ref 6)	1	5	yes
7	Offshore W*(ref 6)	1	5	yes
8	Nuclear ** (ref 4,5)	7	9	yes

* minimum value: for some components, solutions are still at basic principle stage. maximum value: for other components, technologies have been validated in relevant environment but not yet applied at large scale.

** minimum value corresponds to deep geological disposal, which is already under construction in Finland; maximum value corresponds to the well-established and applied technologies in waste management process

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Fiche 1.8.4, Impact of generated wastes - Long-term effect of deposited wastes

Fiche – summary of data and considerations

Category of LCA assessment	Environment
Indicator	1.8 Impact of generated wastes
Sub-indicator	1.8.4 Long-term effect of deposited wastes
Date of release	2023 September 15
Responsible partner	RATEN ICN
Contributing organizations	-
Authors	D. Diaconu
Version	1.0

The following data is compiled from the information and data published in the references listed below.

The long-term effect of the deposited waste has been estimated for entire life cycle of each technology, based on available data in the literature.

The indicator is presented in terms of maximum associated risk.

Table 1 Risk associated to disposed waste generated by energy alternative

		Risk [-]	
		Min	**Max**
1	Coal (ref 1)		2e-4*
2	Gas (NGCC plant)	-	-
3	Hydro	-	-
4	Solar (CSP)	Not assessed yet	
5	Solar (PV)	Not assessed yet	
6	Onshore W	Not assessed yet	
7	Offshore W	Not assessed yet	
8	Nuclear (ref 2, 3)	7.48e-5 (estimated for LIL) 3 x 10–8	10e-3 (observed)
		(estimated for DGD -ref 2)	

* does not account for U and Th carried out by the fly ash.

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Fiche 1.9.1, Impact of accidental situations - Impact of the accidents (anticipated, design base)

Fiche – summary of data and considerations

Category of LCA assessment	Environment
Indicator	Impact of accidental situations
Sub-indicator	Impact of the accidents (anticipated, design base)
Date of release	2023 August 28
Responsible partner	RATEN ICN
Contributing organizations	-
Authors	M. Apostol
Version	1.0

The following information is compiled from (PSAM12), (INSAG10), (NEA), (Wind power-Energy Education), (Hydropower-Energy Education), (Energies 2021), (FEMP), (Hydroreview).

The impact of the accidents (anticipated, design base) on nuclear technology (nuclear installations).

Anticipated operational occurrences (AOOs) are those conditions of normal operation that are expected to occur one or more times during the life of the nuclear power plant (NPP) and should not cause any fuel damage or significant radiation release (PSAM12, 2014). The following examples of AOOs can be given: inadvertent moderator cooldown, loss of normal feedwater, reactor-turbine load mismatch, including loss of load and turbine trip, loss or interruption of core coolant flow excluding reactor coolant pump locked rotor, control rod drop, etc.

To the safety of nuclear installations, the concept of defense in depth, which concerns the protection of both the public and workers, is fundamental. Defense in depth consists in a hierarchical deployment of different levels of equipment and procedures for maintaining the effectiveness of physical barriers (the fuel matrix, fuel cladding, boundary of the reactor coolant system, the containment system) placed between radioactive materials and workers, the public or the environment, in normal operation, anticipated operational occurrences and, for some barriers, in accidents at the plant (INSAG10).

The defense in depth level associated with AOOs is level 2" Control of abnormal operation and detection of failures". This level incorporates inherent plant features, such as core stability and thermal inertia, and systems to control AOOs, with account taken of phenomena able to cause further deterioration in the plant status. The systems to mitigate the consequences of AOOs are designed according to specific criteria such as redundancy, layout, and qualification (INSAG10). In case of anticipated operational occurrences, the objective is to demonstrate that automatic functions and control systems can return the NPP to its normal operating mode as soon as possible and to demonstrate that fuel matrix, fuel clad, and boundary of reactor coolant system remain intact.

Diagnostic tools and equipment such as automatic control systems can be provided to actuate corrective actions before reactor protection limits are reached. Ongoing surveillance of quality and compliance with the design assumptions by means of in-service inspection and periodic testing of systems and plant components is also needed to detect any degradation of equipment and systems before it can affect the safety of the plant (INSAG10).

Design-basis accidents (DBAs) are more serious events that are not expected to occur during the NPP's life. These postulated DBAs establish criteria for the design and evaluation of a variety of safety related systems and equipment. For DBAs, the possibility of limited damage to the fuel is accepted but off-site consequence limitations should not be exceeded (PSAM12, 2014). Therefore, DBAs are postulated accidents in which a nuclear facility must be designed and built to withstand without losing the systems, structures, and components necessary to ensure public health and safety.

The following are some examples of DBAs: the breach of a reactor coolant pipe (loss of coolant accident) or in a main steam line or feedwater line, or loss of control of criticality, such as in a slow uncontrolled boron dilution or a control rod withdrawal (INSAG10).

DBAs represent the third level of defense in depth "Control of accidents within the design basis". Despite provisions for prevention, accident conditions may occur. The key objective is to manage all DBAs in a way they have no (or only minor) radiological consequences (on or off the site), and do not necessitate any off-site protective actions. Engineered safety features and protection systems are provided to prevent evolution towards severe accidents and confine radioactive materials within the containment system. The measures taken at this level aim to prevent core damage in particular. Design and operating procedures are also aimed at maintaining the effectiveness of the barriers, especially the containment, in the event of DBAs. Active and passive engineered safety systems are used. In the short term, safety systems are actuated by the reactor protection system when needed.

The impact of the accidents (anticipated, design base) on renewable technology

Starting from the definition of AOOs from nuclear technology, it can assume that anticipated operational occurrences in the context of renewable technology refers to events or incidents which are expected to happen during the normal operation of renewable energy systems or technologies. They can include deviations from normal operation, such as fluctuations in power output, equipment malfunctions, or human errors.

The following are some examples representing AOOs from different renewable technologies (NEA), (Wind power-Energy Education), (Hydropower-Energy Education):

- Seasonal variations in solar photovoltaic (PV): solar PV generation is higher in the summer than the winter due to longer days;
- Shading: the performance of a solar PV system is affected by shading of the solar panels;
- day-night cycle: daily variation in solar energy generation due to the availability of sunlight during the day and absence at night;
- fluctuation in wind speed: low wind speed may result in reduced energy generation;
- the limits of the wind speeds range (cut-in speed and cut-out speed): activation and deactivation thresholds of the turbine based on wind speeds to prevent damage in high or low wind conditions;
- water flow variation: changes in water flow rates due to seasonal rainfall patterns;
- dam's management: adjustments in dam releases.

Some possible impacts of AOOs refer to: reduced performance or efficiency of renewable energy generation or transmission; reduced availability or reliability of renewable energy supply or grid integration; increased costs or delays due to repairs, replacements, or inspections, etc.

Design basis accidents (DBAs) are events or incidents which are considered in the design and safety analysis of a renewable energy technology or any other complex engineering systems. They are used to establish the design basis for the technology and to ensure that the plants/systems can withstand and mitigate the effects of these accidents while minimizing risks to personnel, the environment, and surrounding communities.

Examples of DBAs (Energies 2021), (FEMP), (Hydroreview):

- extreme wind loads: designing the wind turbine to withstand extreme weather conditions (high winds, lightning strikes);
- wind turbine blade failures;
- extreme weather events (hurricanes, tornadoes, hail, etc.): designing solar panels to resist damages from these events and to maintain their efficiency and structural integrity;
- fire in PV systems due to electrical faults, overheating, or external causes;
- spillway failures and gate malfunctions in the context of hydropower;
- low water levels: designing hydropower plants to address low water flow or drought while ensuring turbine and generator protection.

Some possible impacts of DBAs refer to: safety hazards, environmental damage, damage of equipment, buildings and surrounding natural resources, temporary or prolonged interruptions in electricity production, unplanned shutdowns and operational delays, financial losses, emergency response efforts to ensure the safety of personnel, minimizing environmental damage, and preventing further escalation of the accident.

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Fiche 1.9.2, Impact of accidental situations - Impact of severe accidents (considering mitigation/prevention…)

Fiche – summary of data and considerations

Category of LCA assessment	Environment
Indicator	Impact of accidental situations
Sub-indicator	Impact of severe accidents (considering mitigation/prevention…)
Date of release	2023 August 24
Responsible partner	RATEN ICN
Contributing organizations	-
Authors	M. Apostol
Version	1.0

The following information is compiled from (Research on Severe Accidents in Nuclear Power Plants), (Technical assessment of nuclear energy, 2021), (Science of the Total Environment, 2014), (IAEA-SSG-54, 2019), (IPCC, 2018), (BBC, 2023).

The impact of severe accidents on both nuclear and renewable technologies is presented.

In the nuclear field, severe accidents (SA) are those events with extremely low probability of occurrence but causing significant damage of the reactor core, with more or less complete core meltdown and finally possible serious consequences in case of release of radioactive products into the environment. The severe accidents cannot be excluded with 100% certainty. They are generally caused by a cooling failure within the reactor cooling system (RCS), which prevents proper evacuation of residual power from the core, and by multiple dysfunctions, arising from equipment failure and/or human errors, including the failure of safety procedures (Research on Severe Accidents in Nuclear Power Plants).

The most known SA with core melt, occurred in nuclear power plants (NPP) with a serious impact on the people's health, environment, socio-economic, political and public perception are Three Mile Island (1979, USA), Chernobyl (1986, Soviet Union) and Fukushima (2011, Japan) (Technical assessment of nuclear energy, 2021).

SA can have serious immediate and long-term impacts, but mitigation and prevention strategies play an important role in minimizing these impacts.

The key points on the impacts of SA refer to:

- the release of radioactive material into environment resulting in air, water, soil and agricultural products contamination; the radioactive isotopes released during the SA can remain in the environment for many years, affecting ecosystems, wildlife and potentially entering the food chain;
- the release can affect both the workers from the facilities and the surrounding population;
- health issues: radiation sickness (nausea, burns, organs failure, death) can occur when expose to high levels of radiation; in case of long-term exposure, the risk of cancer and even genetic mutations can increase;
- evacuation of nearby populations to prevent exposure;
- the decommissioning of damaged reactors, cleanup efforts, compensation for affected individuals;
- mistrust of the public in nuclear technology as well as non-radiation-induced diseases such as anxiety, depressions or posttraumatic stress (Science of the Total Environment, 2014).

Learning from the past accidents (Chernobyl, Fukushima), to prevent or mitigate SA, the existing nuclear power plants have implemented enhanced safety measures (redundant safety systems, emergency response plans, better containment structures). To protect the public and the environment from the consequences of a SA, each plant operator establishes a severe accident management program, kept under constant review and development (IAEA-SSG-54, 2019).

The new reactor designs incorporate passive safety features that rely on natural processes to cool the reactor and prevent the core damage in case of power loss. The improved control mechanisms and containment structures are also examples of safety measures which can withstand different accident scenarios (IPCC, 2018).

A severe accident in the context of renewable technology is an event that causes significant adverse impact on human health, the environment or the energy system itself (IPCC, 2018). Severe accidents can occur in various types of renewable energy technologies: solar, wind, hydroelectric, geothermal, biomass systems. These accidents can be triggered by a variety of factors, including equipment malfunction, extreme weather events, design flaws, human errors, or unexpected interactions between components.

Some examples of SA in renewable energy systems are dam failures, biomass fires, wind turbine collapses, solar panel explosions. The likelihood and consequences of such accidents are generally much lower compared to nuclear power.

The impacts of SA can vary, depending on the specific technology involved. For example, severe accidents related to hydropower involve dam failures, resulting from earthquakes, extreme flooding, inadequate maintenance or war - as the recent case of Ukraina's Nova Kakhovka dam (BBC, 2023). Dam failures lead to devastating downstream flooding, environmental damage, loss of life, evacuation of people. An exemple of such as SA is Banqiao dam failure in China, 1975 (IPCC, 2018). Accidents like fires in large solar power plants may results in solar panels damage or damage of electrical infrastructure, going to temporary shutdown and repair costs.

There are different ways to prevent severe accidents in renewable energy systems, such as:

- implementation of safety standards and regulation for the design, construction, operation, maintenance and decommissioning of renewable energy facilities;
- continuous inspection, monitoring and maintenance, for identifying the potential issues before they evolve into severe accidents;
- development of comprehensive emergency response plans specific to each type of renewable technology (the plans should cover scenarios such as equipment failures, natural disasters, hazardous material releases).

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Fiche 1.10.1, Mitigation of accidents - Inherent safety

Fiche – summary of data and considerations

Category of LCA assessment	Environment
Indicator	Mitigation of accidents
Sub-indicator	Inherent safety
Date of release	2023 August 30
Responsible partner	RATEN ICN
Contributing organizations	-
Authors	M. Apostol
Version	1.0

The following information is compiled from (SSR-2/1, 2016), (Safety), (ISAM, 2011), (Canteach), (CANDU6 Design), (IAEA-SSG-54, 2019), (ALFRED White Book), (IAEA -SRS 123), (Cambridge), (Energy), (Practical Engineering).

For nuclear power plants (NPPs) the safety objectives are ensured by fulfillment of the three fundamental safety functions: (1) Control of reactivity, (2) Removal of heat from the fuel, and (3) Confinement of radioactive materials and control of operational discharges, as well as limitation of accidental releases for all operational, accidental and post accidental conditions, within the design basis (SSR-2/1, 2016).

Inherent safety is an approach that aims to achieve the safety by elimination or exclusion of the potential hazards through the fundamental conceptual design choices made for the nuclear plant.

Inherent safety feature (ISF) represents fundamental property of a design concept that results from the basic choices in the materials used or in other aspects of the design which assures that a particular potential hazard cannot become a safety concern in any way (ISAM, 2011). ISF provide a higher level of safety by relying on natural physical phenomena and properties to control and mitigate potential accidents or failures. Inherent means something that exists "as an essential constituent or characteristic" (Safety). Therefore, safety is built into the phenomena, properties of materials, of primary coolants, etc., not added on.

ISF are intended to reduce the likelihood of accidents and mitigate their potential consequences. Significantly enhance the safety on nuclear systems, but they do not eliminate all risks. Bellow, some inherent safety features are presented (Canteach), (CANDU6 Design), (IAEA-SSG-54, 2019), (ALFRED White Book), (IAEA -SRS 123):

- Negative temperature coefficient of reactivity: Temperature coefficient of reactivity is an important inherent safety feature. It represents the change in reactivity per degree of change in the temperature of nuclear fuel, moderator and coolant. A negative reactivity coefficient ensures the reactor can stabilize the power when operation conditions changes, such as fuel and moderator temperature increase when the power increases;
- Criticality of CANDU bundles in ordinary (light) water is not possible, removing a concern in severe accidents;
- The use of natural uranium fuel and heavy water (for CANDU6 type reactors), leads to a design characterized by good neutron economy and low excess reactivity;
- The calandria vessel (again for CANDU6 type reactors) is surrounded by a shield tank containing light water for biological and thermal shielding. In severe core damage accidents, this tank also absorbs decay heat either from the moderator liquid or from direct conduction from debris inside the calandria vessel;

- Passive cooling: cooling systems use natural convection, radiation and other physical processes to remove the heat from the reactor core in case of an accident or shutdown. These systems operate with no need for external power or operator intervention;
- Natural circulation: instead of using the forced circulation by pumps, the NPPs designs rely on natural circulation of coolant due to density differences caused by temperature gradients. This means that cooling can continue even if the pumps fail;
- Core catchers: represent structures designed to capture and contain the molten core material in a severe accident, preventing it from breaching the containment and reducing the risk of widespread radioactive release;
- Accident tolerant fuel (ATF): ATF used in evolutionary and innovative designs is much less susceptible to corrosion or high-temperature oxidation than standard Water-Cooled Reactors fuel;
- Small modular reactors (SMR): the design of SMR allows small reactors which are easier to be managed and cooled in case of an accident. They use passive cooling, natural circulation and other inherent safety features;
- Inherent properties of Lead, when used as coolant in Generation IV - Lead Fast Reactor technology: high boiling point, lack of exothermic reactions with water/air, excellent neutronics properties, retention of radionuclides, shielding properties, etc.

In renewable technology, inherent safety refers to the built-in design features and characteristics of renewable energy systems that minimize the potential for accidents, hazards, and negative impacts on human health, the environment, and infrastructure. The inherent safety features (ISFs) are integrated into the technology itself and are designed to mitigate accidents and minimize risks. In the following, some examples of these ISFs are presented (Cambridge), (Energy), (Practical Engineering):

- Solar panels have a passive operation, contain parts which are not moving. In this way the risk of mechanical failures or accidents is reduced;
- The use of non-toxic materials in solar panels can reduce the risk associated with handling and disposal of hazardous substances;
- Wind turbines are equipped with automatic shut-down mechanisms that activate during high wind speeds or severe weather conditions to prevent damage;
- Hydropower dams are designed with spillways to release the water in excess and prevent overtopping, in this way reducing the risk of dam failure and flooding.

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Fiche 1.10.2, Mitigation of accidents - Passive systems

Fiche – summary of data and considerations

Category of LCA assessment	Environment
Indicator	Mitigation of accidents
Sub-indicator	Passive systems
Date of release	2023 September 1
Responsible partner	RATEN ICN
Contributing organizations	-
Authors	M. Apostol
Version	1.0

The following information is compiled from (IAEA-TECDOC 1485), (IAEA-TECDOC 1624), (Burgazzi, 2012), (ALFRED White Book), *(Applied Sciences),* (IEEE-Green)

Since the mid-1980s it has been recognized that the application of passive safety systems can contribute to simplification and potentially improve economics of new nuclear power plant designs. Passive safety features have been used in nuclear power plants for many decades to accomplish safety functions without requiring an active power source.

Older common reactor designs use passive safety systems to a limited extent, rather relying on active safety systems such as diesel-powered motors. For Generation III and III+ reactors, the evolution was characterized by a more standardized design, an increased utilization of the nuclear fuel, a longer operational lifetime and a more structured safety approach. For the latter, safety goals were fulfilled in different ways, one of them being using passive safety systems. Passive safety systems find and are expected to find applications in the Generation IV reactors concepts, as identified by the Generation IV International Forum (GIF), and also in Small Modular Reactors (SMR) designs.

An important motivation for the use of passive safety systems is the potential for enhanced safety through increased safety system reliability and for reducing the likelihood and consequences of accidents. Design Requirements of the IAEA Safety Standards mention that following a postulated initiating event, the plant is rendered safe by passive safety features or by the action of safety systems that are continuously operating in the state necessary to control the postulated initiating event. (IAEA-TECDOC 1624).

Passive systems represent either systems which are composed entirely of passive components and structures or systems which use active components in a very limited way to initiate subsequent passive operation (IAEA-TECDOC 1485). Passive components do not need any external input or energy to operate and they rely only upon natural physical laws (gravity, natural convection, conduction, etc.) and/or on inherent characteristics (properties of materials, internally stored energy, etc.) and/or ‘intelligent’ use of the energy that is inherently available in the system (decay heat, chemical reactions etc.). The passive safety systems in their designs rely on natural forces, such as gravity or natural convection, to perform their accident prevention and mitigation functions once actuated and started (Burgazzi, 2012).

There are four categories established to distinguish the different degrees of passivity (IAEA-TECDOC 1624):

- Category A (e.g., pipe wall, concrete building). It is characterized by no signal inputs of ‘intelligence’ (such as a signal or parametric change to initiate action), no external power sources or forces, no moving mechanical parts, and no moving working fluid. Examples of safety features included in this category are physical barriers against the release of fission products (such as nuclear fuel cladding and pressure boundary systems), hardened building structures for the plant protection against seismic and or other external events, static components of safety related passive systems (tubes, pressurizers, accumulators, surge tanks), as well as structural parts (supports, shields), etc.;

- Category B (e.g., cooling by free convection) which is characterized by no signal inputs of 'intelligence', no external power sources or forces, no moving mechanical parts, but moving working fluids. Examples of safety features included in this category are reactor shutdown, reactor emergency cooling systems based on air or water natural circulation in heat exchangers immersed in water pools (inside containment) to which the decay heat is directly transferred, containment cooling systems based on natural circulation of air flowing around the containment walls, with intake and exhaust through a stack or in tubes covering the inner walls of silos of underground reactors, etc.;
- Category C (e.g., check valves). It is characterized by no signal inputs of 'intelligence', no external power sources or forces, but moving mechanical parts, whether or not moving working fluids are also present. Examples of safety features included in this category are emergency injection systems consisting of accumulators or storage tanks and discharge lines equipped with check valves, overpressure protection and/or emergency cooling devices of pressure boundary systems based on fluid release through relief valves, mechanical actuators (check valves and spring-loaded relief valves), some trip mechanisms (temperature, pressure and level actuators), etc.;
- Category D (passive execution/active actuation, e.g., scram systems) which is characterized by signal inputs of 'intelligence' to initiate the passive process, energy to initiate the process must be from stored sources such as batteries or elevated fluids, active components are limited to controls, instrumentation and valves to initiate the passive system, manual initiation is excluded. Examples of safety features included in this category are emergency core cooling and injection systems based on gravity that are initiated by battery-powered electric or electro-pneumatic valves, emergency reactor shutdown systems based on gravity or static pressure driven control rods.

In advanced water-cooled nuclear power plant designs (Advanced Boiling Water Reactors, Advanced CANDU Reactors, Advanced Heavy Water Reactors, Advanced Pressurized Water Reactors, etc.) there are passive systems for (IAEA-TECDOC-1485):

- removing the decay heat from the core after a reactor scram;
- removing the heat from the containment and reducing pressure inside containment subsequent to a loss of coolant accident.

The types of passive safety systems considered for core decay heat removal are as follows: pre-pressurized core flooding tanks (accumulators), elevated tank natural circulation loops (core make-up tanks), gravity drain tanks, passively cooled steam generator natural circulation, passive residual heat removal heat exchangers, passively cooled core isolation condensers, sump natural circulation.

The types of passive safety systems for containment cooling and pressure suppression are: containment pressure suppression pools, containment passive heat removal/pressure suppression systems, passive containment spray.

For water cooled SMRs, broad incorporation of passive safety features and passive systems is typical of these designs. The designers of gas cooled SMRs (High Temperature Gas-cooled Reactors - HTGRs) rely on strong reliance on the inherent and passive safety features common to all HTGRs, including large temperature margin of coated particle fuel, exceptional passive shutdown and decay heat removal capability, slow and stable response to transients caused by internal and external initiating events (due to large heat capacity of core graphite) (IAEA-TECDOC-1485).

In the design of Advanced Lead-cooled Fast Reactor European Demonstrator (ALFRED), the demonstrator of Generation IV Lead Fast Reactor (LFR) technology and the prototype of an LFR-based SMR concept, passive systems are used, which are based on natural physical processes for their actuation and operation with no reliance on active components such as pumps, fans, or diesel generators. These passive systems are designed to function without safety-grade support systems such as AC power and component cooling water (ALFRED White Book).

Passive systems play an important role in accidents mitigating and enhance safety in different renewable technology. Below*, some elements to be considered in the assessment of the sub-indicator "Passive systems" for solar and wind technologies are presented.*

For solar cells, passive cooling systems are used for maintaining optimal operating temperatures for solar panels. Some of the passive cooling methods commonly used include adding heat sinks, adding a phase change material, and cooling solar cells with a floating system on water. Passive solar panel cooling has the advantage of not requiring additional power and represent solution to the problem of solar cells overheating (Applied Sciences).

Wind turbine systems are complex and remotely installed structures which are also subject to many possible faults in the existed components. Early fault detection, isolation and successful controller reconfiguration can considerably increase the performance in faulty conditions and prevent failures in the system. Fault identification determines the type of fault and its severity. In passive fault-tolerant control, a fixed controller is designed that tolerates changes of the plant dynamics. The controlled system satisfies its goals under all faulty conditions. Fault tolerance is obtained without changing controller parameters. It is therefore called passive fault-tolerant (IEEE-Green).

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Fiche 1.10.3, Mitigation of accidents - Safety by design

Fiche – summary of data and considerations

Category of LCA assessment	Environment
Indicator	Mitigation of accidents
Sub-indicator	Safety by design
Date of release	2023 September 9
Responsible partner	RATEN ICN
Contributing organizations	-
Authors	M. Apostol
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The following information is compiled from (Britsafe), (GIF/RSWG/2021/001), (ISAM2011), (IAEA-glossary, 2022), (windpowerengineering), (windpower).

Safety by design "is the concept of making work processes and systems inherently safe by preemptively eliminating risks and hazards from them. It is a preventive approach towards safety that entails identifying potential risks involved in an existing or proposed work system and eliminating these risks by making necessary changes. These changes can be associated with equipment, structures, tools, as well as work methods. The resulting work system, be it a factory or a front office, is free of all recognized health and safety risks, thereby minimizing the likelihood of harm to human health and life". Safety by design follows the following axiom: "Get it right the first time" (Britsafe).

Starting from this definition, it can be said that in nuclear field, safety by design represents an approach in the development and operation of nuclear facilities which incorporates safety features and considerations at different stage of the design to mitigate accidents and minimize their potential consequences, in this way resulting an enhanced safety of the facilities.

The level of safety that has been attained by the majority of Generation II operating nuclear power plants in most countries of the world is already very good. In parallel, the quantitative safety objectives applicable to the reactors of the third generation (e.g., Advanced Passive Pressurized Water Reactor - AP1000 and European Pressurized Reactor - EPR) are very ambitious and assure an improved level of protection reducing the level of risk in a demonstrable way. For Generation III reactors, the lessons learnt from the Fukushima accident has been taken into account and these lessons must also be considered at the design stage for Generation IV (GenIV) reactors (GIF/RSWG/2021/001). The considerations are needed to be taken into account, also for Small Modular Reactors (SMR) design stages.

Early generations of nuclear technology generally applied system safety analysis techniques to relatively mature designs. In many cases, reactors were fully designed, built, and operate before methods that are today recognized as system safety analysis tools were applied to identify and evaluate safety vulnerabilities associated with these systems. The result, in many cases, was addition of design "backfits" developed to reduce safety vulnerabilities discovered through operating experience or through analysis (ISAM2011).

For GenIV nuclear reactors, measurable safety improvements might be achieved in different ways and one of the most important fundamental means lies in the concept of safety that is "built-in, not added-on." By this concept, GenIV designs are developed from the earliest stages in a way that is guided by insights that are derived, e.g., from Probabilistic Safety Assessment (PSA) and other formal safety assessment methods.

The result is a robust design, with no dominant vulnerabilities, and for which no safety-related "add-ons" are needed to achieve a desired level of safety (GIF/RSWG/2021/001).

Below, some ways in which safety by design is implemented for Gen IV nuclear safety improvement (IAEA-glossary, 2022), (GIF/RSWG/2021/001), (ISAM2011) are presented:

- Defence in Depth (DiD): this concept has served the nuclear power industry well, and it must be preserved in the design of Generation IV systems. It is fundamental to nuclear safety and represents a hierarchical deployment of different levels of various equipment and procedures to prevent the escalation of anticipated operational occurrences (AOO) and to maintain the effectiveness of physical barriers placed between a radiation source or radioactive material and workers, public or the environment, in operational states and, for some barriers, in accident conditions. DiD ensures that if a barrier or system fails, there are additional layers of protection to prevent the release of radioactive materials. There are 5 levels of DiD. Level1 is called "Prevention of abnormal operation and failures", Level 2 is defined as "Control of abnormal operation and detection of failures, Level 3 represents the "Control of accidents within the design basis", Level 4 means "Control of severe plant conditions, including prevention of accident progression and mitigation of the consequences of severe accidents" and Level 5 is defined as "Mitigation of radiological consequences of significant releases of radioactive material".
- Minimization of sensitivity to human errors: Human error is an imbalance between what the situation requires, what the person intends, and what the person does. The reducing of human errors can be made by designing systems, human-machine interfaces, procedures, etc. which are intuitive, user-friendly and errors-resistance. Gen IV systems would seek to retain the most positive aspects of the human-machine interface, but to minimize the possibility for human errors.
- Improved reliability: a high reliability of plant systems can be achieved in different ways, such as using of new materials, improved maintenance activities, on-line condition monitoring and prognostics, using of passive design features and other inherently safe design provisions, such as gravity, natural convection, conduction, negative reactivity feedback, thermal inertia, and other intrinsic physical processes.
- Deterministic and Phenomenological Analyses (DPA): DPA include thermal-hydraulic analyses, computational fluid dynamics (CFD) analyses, reactor physics analyses, accident simulation, materials behaviour models and structural analysis models. These analyses will be used as needed to understand and quantify the safety issues that must guide concept and design development, and their results will form inputs needed for a credible Probabilistic Safety Assessment (PSA). DPA will be used from the late stage of the pre-conceptual design phase through ultimate licensing and regulation of the Gen IV system.
- Probabilistic Safety Assessment (PSA): safety by design incorporates PSA technique. It provides a structured means of identifying the answers to three basic questions related to safety, which are: What can go wrong? How likely is it they can go wrong? and What are the consequences if they do go wrong? PSA helps in identifying and prioritizing potential accident scenarios based on their probabilities and consequences. PSA is to be performed, and iterated, beginning in the late pre-conceptual design phase, and continuing through the final design stages addressing licensing and regulation concerns.
- Objective Provision Tree (OPT): It provides an exhaustive overview of the safety related architecture and allows the identification, for each level of the DiD, of all provisions that contribute to the achievement of safety functions as well as their mutual interrelations. The OPT's purpose is to ensure and document the implementation of essential "lines of protection" to ensure successful prevention, control or mitigation of phenomena that could potentially damage the nuclear system.

Having again a look at the (Brissafe) definition of safety by design, it can be said that for renewable energy systems, safety by design is an approach that incorporate safety considerations throughout the entire design and development process of renewable energy systems.

In the following, some considerations for accidents mitigation, using safety by design (windpowerengineering), (windpower) are briefly discussed:

- The control of operational risk: the best way to control operational risk is to eliminate hazards during the design of wind turbines, solar panels or other facilities specific to renewable technology. Safety by design integrates hazards identification, risk assessment, and control methods early in design, to eliminate or minimize risks to the long-term integrity of the facilities.
- Redundancy and fail-safe mechanisms: to ensure that if one component or system fails, backup systems are in place to prevent accidents or mitigate their consequences, safety by design incorporates redundant safety features and fail-safe mechanisms.
- Electrical and fire safety: implementation of electrical safety measures to protect workers and prevent electrical accidents (grounding, insulation, circuit protection, etc.). Incorporation of fire detection and suppression systems where the fire risk could be higher. A good ventilation and components separation to minimize fire hazards should be ensured by design.
- Structural integrity and stability: the structural integrity and stability of renewable energy infrastructure (such as wind turbines or solar arrays), should be ensured, to prevent accidents due to component failure or extreme weather conditions. Factors like wind loads, seismic events, or corrosion resistance, should be incorporated into design.

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Fiche 2.1, Capacity factor

Fiche – summary of data and considerations

Category for the assessment	Economics
Indicator	2.1 Capacity factor
Sub-indicator	-
Date of release	2023 September 20
Responsible partner	RATEN ICN
Contributing organizations	-
Authors	C.A. Margeanu
Version	1.0

The capacity factor calculates how efficiently a power plant or fleet of generators is operating overall. The capacity factor is calculated by dividing the yearly output of a power plant (or fleet of generators) by the sum of the output and the number of hours in a specific time frame. In other words, it compares a power plant's actual generation to the greatest amount it might produce without any interruption in a particular time frame. The annual capacity factor measures how many hours in the year the power plant worked as well as what proportion of its total production, as power plants occasionally operate at less than full output.

The annual capacity factor of a power plant is, therefore, a measure of availability (how much hours it is available to generate electricity) and an indirect measure of the marginal cost of generation (for non-variable sources) and other characteristics such as flexibility and startup times.

In order to calculate the capacity factor, the total amount of energy produced by plant in some period is divided by the whole energy the plant would have produced at full capacity. Capacity factors differ with every type of fuel.

The maximum output power of an installation assumes that it will operate continuously at maximum capacity for a predetermined amount of time. The capacity factor at this time and the present energy production varies widely based on a variety of variables.

A power plant would have a capacity factor lower than 100% based on technical constraints (such as availability of the plant), economic reasons, and availability of the energy resource.

A plant can be out of service or operating at reduced output for part of the time due to equipment failures or routine maintenance. This accounts for most of the unused capacity of base load power plants. Base load plants usually have low costs per unit of electricity because they are designed for maximum efficiency and are operated continuously at high output. Geothermal power plants, nuclear power plants, coal-fired plants and bioenergy plants that burn solid material are almost always operated as base load plants, as they can be difficult to adjust to suit demand.

A plant can also have its output curtailed or intentionally left idle because the electricity is not needed or because the price of electricity is too low to make production economical. This accounts for most of the unused capacity of peaking power plants and load following power plants. Peaking plants may operate for only a few hours per year or up to several hours per day. Many other power plants operate only at certain times of the day or year because of variation in loads and electricity prices. If a plant is only needed during the day, for example, even if it operates at full power output from 8 am to 8 pm every day (12 hours) all year long, it would only have a 50% capacity factor. Due to low-capacity factors, electricity from peaking power plants is relatively expensive because the limited generation has to cover the plant fixed costs.

A third reason is that a plant may not have the fuel available to operate all of the time. This can apply to fossil generating stations with restricted fuels supplies, but most of all applies to intermittent renewable resources. Solar PV and wind turbines have a capacity factor limited by the availability of their "fuel", sunshine and wind respectively. A hydroelectricity plant may have a capacity factor lower than 100% due to restriction or scarcity of water, or its output may be regulated to match the current power need, conserving its stored water for later usage.

When hydroelectric plants have water available, they are also useful for load following, because of their high dispatchability. A typical hydroelectric plant's operators can bring it from a stopped condition to full power in just a few minutes.

Wind farms production of electricity is variable, due to the natural variability of the wind. For a wind farm, the capacity factor is determined by the availability of wind, the swept area of the turbine and the size of the generator. Transmission line capacity and electricity demand also affect the capacity factor. Typical capacity factors of current wind farms are between 25 and 45%.

Solar energy is variable because of the daily rotation of the earth (day and night), seasonal changes, and because of cloud cover.

Nuclear power plants are at the top of the range of performance factors, ideally reduced only by the availability of factors, i.e. maintenance and refueling. The formula below gives the annual capacity factor for a NPP (1000 MW total installed capacity) that produced during the year 8.20 TWh.

$$\frac{8200000\ \ MWh}{365\,day \times 24\,h\,/\,day \times 1000\,MW} = 0.936 = 93.6\%$$

The Danish offshore wind farm Horns Rev 2 has an installed capacity of 209.3 MW. Since it was commissioned in January 2017, the wind farm produced 6416 GWh, i.e. an average annual production of 875 GWh/year. The corresponding capacity factor is:

$$\frac{875000\ \ MWh}{365\,day \times 24\,h\,/\,day \times 209.3\,MW} = 0.477 = 47.7\%$$

Calculations may be affected by seasonality, so in Finland, capacity factor during the cold winter months is more than double compared to July.

Hoover Dam has an installed capacity of 2080 MW and an annual generation averaging 4.2 TWh. Taking the average figure for annual generation gives a capacity factor of:

$$\frac{4200000\ \ MWh}{365\,day \times 24\,h\,/\,day \times 2080\,MW} = 0.230 = 23\%$$

At the low range of capacity factors is the photovoltaic power station, which supplies power to the electricity grid from a large-scale photovoltaic system (PV system). An inherent limit to its capacity factor comes from its requirement of daylight, preferably with a sun unobstructed by clouds, smoke or smog, shade from trees and building structures. The amount of sunlight varies both with the time during the day and the seasons of the year, the capacity factor being typically computed on an annual basis. The amount of available sunlight is mostly determined by the latitude of the installation and the local cloud cover. The actual production is also influenced by local factors such as dust and ambient temperature, which ideally should be low.

Agua Caliente Solar Project, located in Arizona, US, has an installed capacity of 290 MW and an actual average annual production of 740 GWh/year. Its capacity factor is:

$$\frac{740000\ \ MWh}{365\,day \times 24\,h\,/\,day \times 290\,MW} = 0.291 = 29.1\%$$

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Fiche 2.2, Global efficiency

Fiche – summary of data and considerations

Category for the assessment	Economics
Indicator	2.2 Global efficiency
Sub-indicator	-
Date of release	2023 September 20
Responsible partner	RATEN ICN
Contributing organizations	-
Authors	C.A. Margeanu
Version	1.0

Energy efficiency is called the "first fuel" in clean energy transitions, as it provides some of the quickest and most cost-effective CO2 mitigation options while lowering energy bills and strengthening energy security. Together, efficiency, electrification, behavioural change and digitalisation shape global energy intensity – the amount of energy required to produce a unit of GDP, a key measure of energy efficiency of the economy.

Energy efficiency is the single largest measure to avoid energy demand in the Net Zero Emissions by 2050 Scenario. Furthermore, most efficiency measures result in cost savings to consumers, lowering energy bills and helping cushion the effects of unexpected price spikes, such as occurred after Russia's invasion of Ukraine.

While efficiency investment has recently been increasing to reach new record levels, the pace of global energy intensity improvements had noticeably slowed in the second half of the last decade and virtually stalled during the first two years of Covid-19. Doubling the global pace of energy efficiency progress this decade is a key step in efforts to reach net zero emissions.

The unparalleled global energy crisis sparked by the Russian invasion of Ukraine has dramatically escalated concerns over energy security and the inflationary impact of higher energy prices on the world's economies. Lowering record-high consumer bills and securing reliable access to supply is a central political and economic imperative for almost all governments. While there are many ways for countries to address the current crisis, focusing on energy efficiency action is the unambiguous first and best response to simultaneously meet affordability, supply security and climate goals. With efforts to conserve and better manage energy consumption in sharp focus since the onset of the crisis, efficiency progress has gained momentum, with annual energy intensity improvements expected to reach about 2% in 2022.

Energy efficiency policies have been strengthened globally in the past year. Countries representing more than 70% of the world's energy consumption have introduced new or strengthened efficiency policies since the start of the current energy crisis.

The European Union agreed to stronger rules to boost energy efficiency in March 2023. These nearly double the rate of annual energy savings EU countries are obliged to deliver on average each year from 2024 to 2030 to 1.49%.

The United States announced important new funding in 2022 under the Inflation Reduction Act (IRA), which is expected to substantially boost energy efficiency actions that bring energy bills down. This includes the USD 4.5 billion High-Efficiency Electric Home Rebate programme which provides up to

USD 14 000 per household for upgrades to heating, cooling, insulation, air sealing and electrical systems including lighting and appliances.

China strengthened its industrial energy efficiency policies in 2022 with new plans to improve the energy intensity of the sector by 13.5% by 2025 compared with 2020 levels, including detailed targets and plans for the 17 most energy intensive industries.

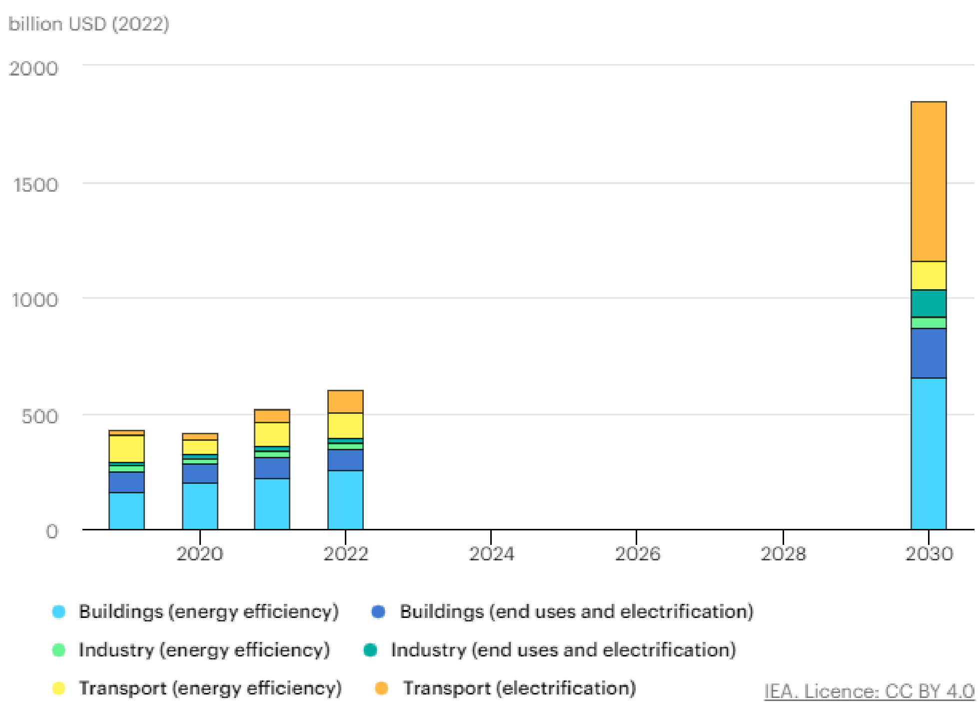
In support of its Lifestyle for Environment Initiative (LiFE), India passed new efficiency laws to strengthen building codes and policies covering appliances, vehicles, industrial facilities and commercial buildings.

Progress on efficiency has accelerated over the past two decades but needs to double for net zero emissions. Energy-efficient technologies slow growth in energy demand and play a vital role in reducing fossil fuel consumption and emissions in all sectors of the economy. For example, more energy-efficient cars, trucks and aircraft reduce oil demand in the transport sector; more efficient steel, cement and chemical manufacturing reduces fossil fuel use in industry; and better insulation and more efficient appliances reduce the electricity and direct fossil fuel consumption of buildings.

Energy efficiency investment increased by 16% to USD 600 billion in 2022 as a result of government stimulus programmes driving spending on efficient buildings and by the growing popularity of electric vehicles. However, investment in energy efficiency is likely to face headwinds in 2023 as higher interest rates slow down economic growth and raise the cost of household borrowing and lending.

In response to the current energy crisis, governments are revisiting energy efficiency targets and policies to reflect increased urgency in a focused effort to lower reliance on high-price fossil fuels, protect consumers from high energy bills and reduce dependency on Russian gas in Europe.

In the figure below, global energy efficiency-related end-use investment in the Net Zero Scenario in the period 2019-2030 is illustrated, according to IEA primary annual analysis on global developments in energy efficiency markets and policy “Energy Efficiency 2022”.



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Fiche 2.3.1, Cost - Cost of the investment (capital cost)

Fiche – summary of data and considerations

Category for the assessment	Economics
Indicator	2.3 Cost
Sub-indicator	2.3.1 Cost of the investment (capital cost)
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Responsible partner	RATEN ICN
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Authors	C.A. Margeanu
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The costs for generating electricity are usually divided into *capital investment (CapInv) costs*, *operating and maintenance (O&M) costs* and *fuel (Fuel) costs*. Information on these costs and on the timing of such expenditures, over the plant lifetime, should be provided by the supplier(s) to the analyst, who discount them using an appropriate discount rate to determine the Net present value (NPV), and hence the levelized cost of electricity (LCOE).

LCOE is the main tool for comparing the plant-level unit costs of various generating technologies with different cost components over their operating lifetimes. Plant-level costs imply that for the LCOE calculation the overall system effects are not taken into account, i.e. the impact of a power plant on the electricity system as a whole. The system effects, however, can potentially have a significant impact.

The capital investment costs include both the overnight (capital) cost per unit of installed capacity and the costs of financing, which depend on the duration of construction, the construction expenditure flow, and the cost of capital. Usually, the investment costs are divided into categories as follows:

- Direct construction costs, or overnight capital costs, ONT (include the overnight construction cost, the contingency and owner costs). It equals the cost of a construction project if no interest was incurred during construction, as if the project was completed 'overnight'. Contingency costs refer to unforeseen or unpredictable costs. Often, the designer can determine an appropriate allowance item by item or as a lump value for all the direct construction costs. The contingency allowance will depend on the maturity level of the design, gaps in engineering knowledge, source of cost estimation and the degree of innovation.
- Indirect construction costs (often include the cost of contracting, design, engineering, inspection, startup, and interest during construction (IDC); cover construction facilities, equipment and services, including buildings and other facilities that are removed after construction has been completed; may include taxes and insurance, if applicable; also include costs for staff training and for plant startup as well as costs incurred by the owner in carrying out the project, such as the costs of licensing, public relations and administrative overheads)
- Backfitting costs (includes all the major refurbishment costs not included in the annual O&M costs, and required to keep the performance of the plant within declared values)
- Decommissioning and waste management costs (are often converted to annual costs and are treated as such, either as a fuel cost or an operating cost or some combination of the two, by calculating the NPV of the funds that have to be set aside on an annual basis to cover the cost of decommissioning and residual waste management costs at the end of plant life.)

A levelized capital cost or levelized amortization cost (LUAC) can be calculated for the different generating technologies:

$$LUAC = \frac{ONT + IDC}{8760 \cdot Lf \cdot \sum_{t=0}^{t_{life}} \frac{1}{(1+r)^t}} + LUAC_{Bf} + LUAC_D$$

[mill$/kWh] or [$/MWh]

ONT= total overnight capital costs;
IDC = interest during construction;
$LUAC_{BF}$ = levelized backfitting cost;
$LUAC_D$ = levelized decommissioning cost;
Lf = load factor of the plant;
8760 = Number of hours in a year = 24x(31x7+30x4+28)
t_{life} = life of the plant;
r = discount rate (it takes time value of money into account, i.e. money earned in future has less value than received today)

Technology	Number of plants / countries	Net capacity (MWe)		Overnight costs (USD/kWe)	
		Min	Max	Min	Max
Lithium-ion battery	4 / 4	1.0	19	452	1 967
Biomass	4 / 3	0.42	30	833	6 545
Biomass (CHP)	5 / 2	0.42	358	2 538	6 545
Coal	11 / 6	138	954	800	4 382
Coal (CCUS)	4 / 2	499	650	4 490	5 991
Coal (CHP)	1 / 1	700	700	2 240	2 240
Fuel cell	4 / 2	0.003	15	2 361	6 492
Gas (CCGT)	16 / 11	471	1 372	254	1 109
Gas (CCGT, CCUS)	2 / 2	437	646	2 412	2 826
Gas (CCGT, CHP)	2 / 2	5.80	500	1 024	1 160
Gas (OCGT/int. comb.)	8 / 5	100	980	325	1 141
Gas (OCGT/int. comb., CHP)	3 / 3	35.90	195	330	1 107
Geothermal	6 / 2	5	40	3 851	10 959
Hydro (reservoir, >= 5 MW)	4 / 4	11.95	175	1 899	5 819
Hydro (reservoir, < 5 MW)	1 / 1	0.32	0.32	3 966	3 966
Hydro (run of river, >= 5 MW)	7 / 4	5	248	2 326	6 681
Hydro (run of river, < 5 MW)	18 / 4	0.02	4.80	956	7 484
Lignite	2 / 2	709	900	2 189	3 756
Lignite (CCUS)	1 / 1	570	570	6 891	6 891
Lignite (CHP)	1 / 1	2 900	2 900	1 015	1 015
Nuclear	8 / 8	950	1 650	2 157	6 920
Nuclear (LTO)	4 / 4	1 000	1 000	391	629
Pumped storage	3 / 3	175	1 000	563	4 426
Solar PV (floating)	1 / 1	8	8	860	860
Solar PV (utility scale)	21 / 14	0.83	100	534	2 006
Solar PV (commercial)	15 / 8	0.05	0.50	846	1 357
Solar PV (residential)	15 / 8	0.004	0.02	719	2 597
Solar thermal (CSP)	4 / 2	100	150	5 238	6 475
Offshore wind	23 / 8	11.25	600	1 721	4 039
Onshore wind (>= 1 MW)	33 / 18	1	280	877	3 022
Onshore wind (< 1 MW)	11 / 1	0.01	0.90	1 782	5 539

Note: CHP = combined heat and power. CCUS = carbon capture. utilisation and storage.
CCGT = Combined cycle gas turbine. OCGT = Open cycle gas turbine.
LTO = long-term operation. CSP = concentrated solar power.

For fossil fuel power plants, one usually assumes zero back fitting and decommissioning costs ($LUAC_{BF}$ and $LUAC_D$). Regular (planned) replacements of main equipment parts can be included in O&M costs. For capital intensive generating technologies (e.g. nuclear) LUAC is the main contributor to LCOE.

In the table below, the size and overnight cost statistics for various technologies are listed, according to the IEA and NEA-OECD joint study "Projected Costs of Generating Electricity. 2020 Edition". The dataset covers a wide range of generating technologies, including: natural gas-fired, coal-fired generation, nuclear power plants, solar photovoltaic (of varying sizes) and concentrated solar power, onshore and offshore wind, geothermal, biomass, and combined heat and power (based on a variety of fuels).

References:

- *IEA, NEA-OECD "Projected Costs of Generating Electricity. 2020 Edition", 2020*
- *NEA-OECD "The Full Costs of Electricity Provision", NEA No. 7298, 2018*
- *IAEA "Economic Evaluation of Alternative Nuclear Energy Systems Economics", IAEA-TECDOC-2014, 2022*

IAEA "INPRO Methodology for Sustainability Assessment of Nuclear Energy Systems: Economics", IAEA Nuclear Energy Series, No. NG-T-4.4, 2014

Fiche 2.3.2, Cost - Cost of operation (including fueling and maintenance)

Fiche – summary of data and considerations

Category for the assessment	Economics
Indicator	2.3 Cost
Sub-indicator	2.3.2 Cost of operation (including fueling and maintenance)
Date of release	2023 September 20
Responsible partner	RATEN ICN
Contributing organizations	-
Authors	C.A. Margeanu
Version	1.0

The costs for generating electricity are usually divided into *capital investment costs*, *operating and maintenance (O&M) costs* and *fuel (Fuel) costs*. Information on these costs and on the timing of such expenditures, over the plant lifetime, should be provided by the supplier(s) to the analyst, who discount them using an appropriate discount rate to determine the Net present value (NPV), and hence the levelized cost of electricity (LCOE).

LCOE is the main tool for comparing the plant-level unit costs of various generating technologies with different cost components over their operating lifetimes. Plant-level costs imply that for the LCOE calculation the overall system effects are not taken into account, i.e. the impact of a power plant on the electricity system as a whole. The system effects, however, can potentially have a significant impact.

The cost of operation includes both the O&M costs and Fuel costs. However, in most approaches for generating electricity costs calculation these types of costs are treated separately.

O&M costs are usually divided into variable O&M costs, including those that depend on the amount of energy generated, and fixed O&M costs, including those that do not depend on the energy generated each year (e.g. staff salaries, auxiliary equipment and materials purchasing, refurbishment of buildings and equipment, non-fuel waste management, etc.). Usually variable O&M costs are proportional to the annual electricity output. Miscellaneous O&M costs include items such as public relations, training, rents, and travel. It also includes liability insurance and the fixed charges for the working capital to pay for items in the O&M category.

A levelized cost of O&M (LUOM) can be calculated for the different generating technologies, assuming that O&M expenses are distributed evenly by year, and net electric power and load factor are constant:

$$LUOM = \frac{O\&M}{P \cdot 8760 \cdot Lf} = \frac{(O\&M)_{fix}}{8760 \cdot Lf} + (O\&M)_{var}$$

[mill$/kWh] or [$/MWh]

$(O\&M)_{fix}$ = fixed O&M costs;
$(O\&M)_{var}$ = variable O&M costs;
P = net electric power of the plant;
Lf = load factor of the plant;
8760 = number of hours in a year = 24x(31x7+30x4+28)

Fuel element costs for nuclear power plants include: *fuel material costs* (costs of mining, milling and processing the original ore, and, for enriched fuels, the costs for enrichment and conversion), *cost of manufacturing fuel elements and processing of the irradiated material* (larger production volumes lead to lower unit costs so purchasing fuel from a manufacture supplying many units would be expected to be significantly cheaper than building a dedicated plant to supply a small number of units), *fuel loading costs* (cost for the first reactor core and the costs for routine refuelling), *spent fuel management cost*, and the *reprocessing cost*. Since the time required for one complete fuel cycle operation could be of 2–6 years, levelized costs are sensitive to the discount rate used and the timing of expenditures.

The levelized cost of the nuclear fuel, LUFC, is composed by both front-end and back-end fuel costs:

$$LUFC_{nuclear} = \frac{FC_1}{\eta \cdot \delta \cdot 8760 \cdot Lf \cdot \sum_{t=0}^{t_{life}} \frac{1}{(1+r)^t}} + \frac{FC_{re}}{Q \cdot \eta} + \frac{SF}{Q \cdot \eta}$$

[mill$/kWh] or [$/MWh]

FC_1 = levelized fuel front end costs for the first core; FC_{re} = levelized fuel costs for the reload core;
η = net thermal efficiency of the plant; δ = average power density in reactor core at full power;
Q= average burnup of unloaded fuel; *SF*= fuel back end cost
Lf = load factor of the plant; 8760 = Number of hours in a year = 24x(31x7+30x4+28)
t_{life} = life of the plant; *r* = discount rate (it takes time value of money into account, i.e. money earned in future has less value than received today).

The fuel costs calculation for fossil plants is significantly different, an important feature being their heavy dependence on the fuel cost, which may escalate rapidly.

$$LUFC = \frac{F_0}{P \cdot 8760 \cdot Lf} \cdot \frac{\sum_{t=0}^{t_{end}} \left(\frac{1+i}{1+r}\right)^t}{\sum_{t=0}^{t_{end}} \frac{1}{(1+r)^t}} = \frac{3600 \cdot FS}{\eta} \cdot \frac{\sum_{t=0}^{t_{end}} \left(\frac{1+i}{1+r}\right)^t}{\sum_{t=0}^{t_{end}} \frac{1}{(1+r)^t}}$$

[mill$/kWh] or [$/MWh]

F_0 = price of fuel to be spent per year at t = 0; *FS* = specific price of fuel at t = 0;
P = net electric power of the plant; η = net thermal efficiency of the plant;
Lf = load factor of the plant; 8760 = number of hours in a year = 24x(31x7+30x4+28)
i = escalation rate; 3600 = conversion factor from joules into watt-hours;
t_{end} =end of lifetime of the plant *r* = discount rate (it takes time value of money into account, i.e. money earned in future has less value than received today).

The tables below present the electricity generation technology costs characterizing several regions selected for analysis by the IEA and IRENA Renewable Costing Alliance in “World Energy Outlook 2022”, for two scenarios, namely Stated Policies Scenario (STEPS) and Net Zero Emissions by 2050 (NZE). The assumptions about public health and economic recovery implications across the scenarios were similar.

STEPS Scenario	Capital costs (USD/kW)			Capacity factor (%)			Fuel, CO_2, O&M (USD/MWh)			LCOE (USD/MWh)		
	2021	2030	2050	2021	2030	2050	2021	2030	2050	2021	2030	2050
United States												
Nuclear	5 000	4 800	4 500	90	90	90	30	30	30	105	100	95
Coal	2 100	2 100	2 100	35	15	n.a.	25	25	25	95	210	n.a.
Gas CCGT	1 000	1 000	1 000	55	40	20	35	40	40	60	70	110
Solar PV	1 090	710	510	21	22	23	10	10	10	50	30	25
Wind onshore	1 380	1 310	1 250	42	43	44	10	10	10	35	30	30
Wind offshore	4 040	2 460	1 820	42	46	49	35	20	15	120	70	50
European Union												
Nuclear	6 600	5 100	4 500	80	80	80	35	35	35	140	120	105
Coal	2 000	2 000	2 000	40	20	n.a.	115	130	140	180	255	n.a.
Gas CCGT	1 000	1 000	1 000	20	10	n.a.	100	120	130	155	270	n.a.
Solar PV	810	530	410	14	14	14	10	10	10	50	35	30
Wind onshore	1 590	1 510	1 450	29	30	30	15	15	15	55	50	45
Wind offshore	3 040	2 000	1 500	51	56	59	15	10	10	60	40	30
China												
Nuclear	2 800	2 800	2 500	80	80	80	25	25	25	65	65	60
Coal	800	800	800	60	50	35	60	60	70	75	80	95
Gas CCGT	560	560	560	35	25	20	95	105	115	115	130	140
Solar PV	630	410	300	17	18	19	10	5	5	35	20	15
Wind onshore	1 160	1 090	1 050	26	27	28	15	10	10	45	40	40
Wind offshore	2 860	1 840	1 380	33	39	43	25	15	10	100	55	40
India												
Nuclear	2 800	2 800	2 800	75	85	90	30	30	30	75	65	65
Coal	1 200	1 200	1 200	65	75	75	40	35	35	60	55	50
Gas CCGT	700	700	700	40	50	45	75	85	85	95	100	105
Solar PV	590	380	270	20	21	22	5	5	5	35	20	15
Wind onshore	930	880	830	26	28	30	10	10	10	45	40	35
Wind offshore	2 780	1 820	1 300	33	37	39	25	15	10	120	75	50

STEPS do not take for granted that governments will reach all announced goals. Instead, it explores where the energy system might go without additional policy implementation. It takes a granular, sector-by-sector look at existing policies and measures and those under development.

NZE shows a narrow but achievable pathway for the global energy sector to achieve net zero CO_2 emissions by 2050, with advanced economies reaching net zero emissions in advance of the other scenarios. This scenario also meets key energy-related United Nations Sustainable Development Goals (SDGs), in particular achieving universal energy access by 2030.

In some approaches, decommissioning and waste management costs are often converted to annual costs and are treated as such, either as a fuel cost or an operating cost or some combination of the two, by calculating the NPV of the funds that have to be set aside on an annual basis to cover the cost of decommissioning and residual waste management costs at the end of plant life.

NZE Scenario	Capital costs (USD/kW)			Capacity factor (%)			Fuel, CO_2 and O&M (USD/MWh)			LCOE (USD/MWh)		
	2021	2030	2050	2021	2030	2050	2021	2030	2050	2021	2030	2050
United States												
Nuclear	5 000	4 800	4 500	90	90	85	30	30	30	100	100	100
Coal	2 100	2 100	2 100	30	n.a.	n.a.	85	155	220	165	n.a.	n.a.
Gas CCGT	1 000	1 000	1 000	50	25	n.a.	55	80	105	80	130	n.a.
Solar PV	1 090	620	430	21	22	23	10	10	10	50	30	25
Wind onshore	1 380	1 270	1 190	42	43	44	10	10	10	35	30	30
Wind offshore	4 040	2 200	1 500	42	46	49	35	20	15	120	60	40
European Union												
Nuclear	6 600	5 100	4 500	80	80	70	35	35	35	140	115	115
Coal	2 000	2 000	2 000	25	n.a.	n.a.	135	185	250	230	n.a.	n.a.
Gas CCGT	1 000	1 000	1 000	25	15	n.a.	95	115	135	145	195	n.a.
Solar PV	810	470	340	14	14	14	10	10	10	50	35	25
Wind onshore	1 590	1 470	1 380	29	30	30	15	15	15	55	50	45
Wind offshore	3 040	1 800	1 240	51	56	59	15	10	5	60	35	25
China												
Nuclear	2 800	2 800	2 500	85	80	70	25	25	25	65	65	65
Coal	800	800	800	55	n.a.	n.a.	80	120	180	100	n.a.	n.a.
Gas CCGT	560	560	560	35	25	n.a.	90	110	130	105	130	n.a.
Solar PV	630	360	250	17	18	19	10	5	5	35	20	15
Wind onshore	1 160	1 060	1 000	26	27	28	15	10	10	45	40	35
Wind offshore	2 860	1 640	1 120	33	39	43	25	15	10	100	50	35
India												
Nuclear	2 800	2 800	2 800	70	85	90	30	30	30	75	65	65
Coal	1 200	1 200	1 200	65	n.a.	n.a.	40	105	200	60	n.a.	n.a.
Gas CCGT	700	700	700	40	40	n.a.	55	80	110	75	100	n.a.
Solar PV	590	320	210	20	21	22	5	5	5	35	20	15
Wind onshore	930	840	790	26	28	30	10	10	10	45	35	35
Wind offshore	2 780	1 560	1 080	33	37	39	25	15	10	120	65	45

Fuel expenses are the second major component of nuclear power costs (main contribution came from the capital costs), and the most important cost for fossil fuel plants. The efficiency of power plants determines fuel costs and emission intensity of electricity generation.

References:

- *IEA, NEA-OECD "Projected Costs of Generating Electricity. 2020 Edition", 2020*
- *NEA-OECD "The Full Costs of Electricity Provision", NEA No. 7298, 2018*
- *IAEA "Economic Evaluation of Alternative Nuclear Energy Systems Economics", IAEA-TECDOC-2014, 2022*
- *IAEA "INPRO Methodology for Sustainability Assessment of Nuclear Energy Systems: Economics", IAEA Nuclear Energy Series, No. NG-T-4.4, 2014*
- *IEA "World Energy Outlook 2022", 2022*

Fiche 2.3.3, Cost - Cost of decommissioning (including environmental remediation)

Fiche – summary of data and considerations

Category for the assessment	Economics
Indicator	2.3 Cost
Sub-indicator	2.3.3 Cost of decommissioning (including environmental remediation)
Date of release	2023 September 20
Responsible partner	RATEN ICN
Contributing organizations	-
Authors	C.A. Margeanu
Version	1.0

The costs for generating electricity are usually divided into *capital investment (CapInv) costs*, *operating and maintenance (O&M) costs* and *fuel (Fuel) costs*. Information on these costs and on the timing of such expenditures, over the plant lifetime, should be provided by the supplier(s) to the analyst, who discount them using an appropriate discount rate to determine the Net present value (NPV), and hence the levelized cost of electricity (LCOE).

LCOE is the main tool for comparing the plant-level unit costs of various generating technologies with different cost components over their operating lifetimes. Plant-level costs imply that for the LCOE calculation the overall system effects are not taken into account, i.e. the impact of a power plant on the electricity system as a whole. The system effects, however, can potentially have a significant impact.

Decommissioning is a normal part of the lifecycle of almost all industrial facilities. When the facility no longer serves a useful social or economic purpose, it needs to be dismantled and the site made available for other uses.

Requirements for decommissioning should be considered during design and planning of facilities. The decommissioning plan and associated cost estimates need to be prepared in advance, to ensure that sufficient financial resources are available.

Environmental remediation is the process of removing contaminants from sites (buildings, soil, groundwater, sediment, or surface water) that have been polluted due to industrial, manufacturing, mining, and commercial activities. Remediation involves an all-encompassing step process of land restoration from detection, investigation, assessment, determination of remedial measure, actual clean-up, to site redevelopment. In case of nuclear fuel cycle facilities, environmental remediation refers to reducing radiation exposure from contaminated soil, groundwater or surface water. The aim is not only to eliminate the radiation sources, but also to protect people and the environment against potential harmful effects from exposure to ionizing radiation.

A distinction must be made between *ex situ* and *in situ* environmental remediation. *In situ remediation* concerns techniques like biorestoration, soil washing or extraction, and soil venting, whereas containment techniques prevent contamination to migrate. *Ex situ soil remediation* concerns excavation of contaminated soil, cleaning this soil at an independent location and putting it back after cleaning, possibly at the same location.

The capital investment costs include both the overnight (capital) cost per unit of installed capacity and the costs of financing, which depend on the duration of construction, the construction expenditure flow, and the cost of capital. Among the categories of expenses included in the investment costs, decommissioning and waste management expenses need to be taken into account. However, they are often converted to annual costs and are treated as such, either as a fuel cost or an operating cost or some combination of the two, by calculating the NPV of the funds that have to be set aside on an annual basis to cover the cost of decommissioning and residual waste management costs at the end of plant life.

In the tables below, the decommissioning cost statistics for various technologies and countries are listed, according to the IEA and NEA-OECD joint study "Projected Costs of Generating Electricity. 2020 Edition", for discount rates of 3%, 7% and 10%, respectively. The dataset covers a wide range of generating technologies, including: natural gas-fired, coal-fired generation, nuclear power plants, solar photovoltaic (of varying sizes) and concentrated solar power, onshore and offshore wind, geothermal, biomass, and combined heat and power (based on a variety of fuels).

Coal plants at 85% capacity factor

Country	Technology	Net capacity (MWe)	Electrical conversion efficiency (%)	Decommissioning (USD/MWh)		
				3%	7%	10%
Australia	Supercritical pulverised	722	40%	0.21	0.07	0.03
	Supercritical pulverised (CCUS)	633	30%	0.38	0.14	0.06
	Supercritical pulverised (lignite)	709	32%	0.32	0.11	0.05
	Supercritical pulverised (lignite, CCUS)	570	21%	0.59	0.21	0.09
Japan	Ultra-supercritical	749	41%	0.21	0.07	0.03
Korea	Ultra-supercritical	954	43%	0.10	0.03	0.02
United States	Pulverised	138	36%	0.37	0.13	0.06
	Pulverised	140	36%	0.29	0.10	0.05
	Pulverised	650	40%	0.21	0.08	0.03
	Pulverised (CCUS)	650	31%	0.39	0.14	0.06
	Supercritical pulverised	650	42%	0.22	0.08	0.03
	Supercritical pulverised (CCUS)	650	33%	0.40	0.14	0.06
	Ultra-supercritical	641	43%	0.35	0.13	0.05
	Other coal (CCUS)	499	31%	0.51	0.18	0.08
Non-OECD countries						
Brazil	Other coal (lignite)	900	34%	0.19	0.07	0.03
China	Ultra-supercritical	347	45%	0.06	0.02	0.01
India	Ultra-supercritical	400	45%	0.08	0.03	0.01
	Ultra-supercritical	400	45%	0.07	0.03	0.01

Combined-cycle gas turbine (CCGT) at 85% capacity factor						
Country	Technology	Net capacity (MWe)	Electrical conversion efficiency (%)	Decommissioning (USD/MWh)		
				3%	7%	10%
Australia	CCGT	506	48%	0.13	0.06	0.03
	CCGT (CCUS)	437	41%	0.38	0.18	0.10
Belgium	CCGT	500	60%	0.10	0.05	0.03
	CCGT	500	64%	0.14	0.06	0.04
	CCGT	500	58%	0.13	0.06	0.03
Canada	CCGT	471	57%	0.14	0.07	0.04
Italy	CCGT	790	60%	0.08	0.04	0.02
Japan	CCGT	1 372	56%	0.15	0.07	0.04
Korea	CCGT	491	56%	0.15	0.07	0.04
	CCGT	982	59%	0.11	0.05	0.03
Mexico	CCGT	503	51%	0.09	0.04	0.02
	CCGT	785	60%	0.09	0.04	0.02
	CCGT	835	58%	0.06	0.03	0.02
Romania	CCGT	750	58%	0.11	0.07	0.05
United States	CCGT	727	59%	0.13	0.06	0.03
	CCGT (CCUS)	646	48%	0.33	0.16	0.09
Non-OECD countries						
Brazil	CCGT	980	58%	0.13	0.06	0.03
China	CCGT	475	58%	0.06	0.03	0.01

Open-cycle gas turbine (OCGT) at 30% capacity factor						
Country	Technology	Net capacity (MWe)	Electrical conversion efficiency (%)	Decommissioning (USD/MWh)		
				3%	7%	10%
Autralia	OCGT	537	31%	0.26	0.12	0.07
Belgium	OCGT	350	40%	0.20	0.10	0.05
	OCGT	500	41%	0.26	0.12	0.07
	OCGT	500	38%	0.23	0.11	0.06
Canada	OCGT	100	41%	0.44	0.21	0.11
	OCGT	243	40%	0.20	0.09	0.05
Italy	OCGT	130	37%	0.12	0.06	0.03
Non-OECD countries						
Brazil	OCGT	980	44%	0.28	0.13	0.07

Nuclear plants at 85% capacity factor – New build						
Country	Technology	Net capacity (MWe)	Electrical conversion efficiency (%)	Decommissioning (USD/MWh)		
				3%	7%	10%
France	EPR	1 650	33%	0.36	0.05	0.01
Japan	ALWR	1 152	33%	0.36	0.05	0.01
Korea	ALWR	1 377	36%	0.20	0.03	0.01
Russia	VVER	1 122	38%	0.21	0.03	0.01
Slovak Republic	Other nuclear	1 004	32%	1.80	0.96	0.64
United States	LWR	1 100	33%	0.39	0.05	0.01
Non-OECD countries						
China	LWR	950	33%	0.22	0.03	0.01
India	LWR	950	33%	0.25	0.03	0.01

Nuclear plants at 85% capacity factor – Long-Term Operation (LTO), 10 years						
Country	Technology	Net capacity (MWe)	Electrical conversion efficiency (%)	Decommissioning* (USD/MWh)		
				3%	7%	10%
Switzerland	LTO	1 000	33%	0.71	0.40	0.27
France	LTO	1 000	33%	0.81	0.46	0.30
Sweden	LTO	1 000	33%	0.57	0.32	0.21
United States	LTO	1 000	33%	0.51	0.28	0.19

Nuclear plants at 85% capacity factor – Long-Term Operation (LTO), 20 years						
Country	Technology	Net capacity (MWe)	Electrical conversion efficiency (%)	Decommissioning* (USD/MWh)		
				3%	7%	10%
Switzerland	LTO	1 000	33%	0.29	0.13	0.07
France	LTO	1 000	33%	0.34	0.15	0.08
Sweden	LTO	1 000	33%	0.23	0.10	0.06
United States	LTO	1 000	33%	0.21	0.09	0.05

Wind generators – Onshore						
Country	Technology	Net capacity (MWe)	Capacity factor (%)	Decommissioning (USD/MWh)		
				3%	7%	10%
Austria	Onshore wind (>= 1 MW)	3.00	27%	0.80	0.44	0.27
Australia	Onshore wind (>= 1 MW)	100	42%	0.51	0.28	0.17
Belgium	Onshore wind (>= 1 MW)	5.00	30%	0.74	0.40	0.25
	Onshore wind (>= 1 MW)	30	28%	0.77	0.42	0.26
	Onshore wind (>= 1 MW)	4.50	25%	0.92	0.50	0.31
	Onshore wind (>= 1 MW)	30	28%	0.72	0.39	0.24
Canada	Onshore wind (>= 1 MW)	200	40%	0.51	0.28	0.17
Denmark	Onshore wind (>= 1 MW)	4.48	40%	0.35	0.19	0.12
Finland	Onshore wind (>= 1 MW)	30	40%	0.58	0.31	0.19
France	Onshore wind (>= 1 MW)	50	38%	0.58	0.32	0.20
Italy	Onshore wind (< 1 MW)	0.01	17%	4.61	2.51	1.55
	Onshore wind (< 1 MW)	0.06	33%	2.07	1.13	0.70
	Onshore wind (< 1 MW)	0.10	31%	1.62	0.88	0.54
	Onshore wind (< 1 MW)	0.50	33%	1.19	0.65	0.40
	Onshore wind (< 1 MW)	0.90	48%	0.85	0.46	0.29
	Onshore wind (>= 1 MW)	10	37%	0.58	0.31	0.19
	Onshore wind (>= 1 MW)	20	30%	0.75	0.41	0.25
Japan	Onshore wind (>= 1 MW)	20	20%	1.71	0.93	0.57
Korea	Onshore wind (>= 1 MW)	14.85	23%	1.29	0.70	0.43
Netherlands	Onshore wind (>= 1 MW)	50	48%	0.85	0.51	0.34
Norway	Onshore wind (>= 1 MW)	130	44%	0.32	0.17	0.11
Russia	Onshore wind (>= 1 MW)	60	27%	0.89	0.48	0.30
	Onshore wind (>= 1 MW)	280	27%	0.82	0.44	0.27
Sweden	Onshore wind (>= 1 MW)	5	42%	0.39	0.21	0.13
United States	Onshore wind (>= 1 MW)	100	53%	0.24	0.13	0.08
	Onshore wind (>= 1 MW)	100	47%	0.22	0.12	0.08
	Onshore wind (>= 1 MW)	100	37%	0.37	0.20	0.12
	Onshore wind (>= 1 MW)	100	28%	0.77	0.42	0.26
	Onshore wind (>= 1 MW)	100	18%	1.32	0.72	0.44
Non-OECD countries						
Brazil	Onshore wind (>= 1 MW)	30	47%	0.42	0.23	0.14
China	Onshore wind (>= 1 MW)	50	26%	0.59	0.32	0.20
India	Onshore wind (>= 1 MW)	65	27%	0.34	0.19	0.12

Solar generators							
Country	Technology	Net capacity (MWe)	Capacity factor (%)	Annual efficiency loss (%)	Decommissioning (USD/MWh)		
					10%	3%	7%
Austria	Solar PV (residential)	0.02	11%	0.5%	0.99	0.54	0.33
Australia	Solar PV (utility scale)	100	28%	0.5%	0.50	0.27	0.16
	Solar thermal (CSP)	150	47%	0.0%	1.67	0.91	0.56
Belgium	Solar PV (residential)	0.01	13%	0.5%	2.20	1.19	0.73
	Solar PV (residential)	0.01	12%	0.5%	1.72	0.93	0.57
	Solar PV (utility scale)	1.00	13%	0.5%	1.18	0.64	0.39
Canada	Solar PV (utility scale)	20	25%	0.5%	0.85	0.46	0.28
	Solar PV (utility scale)	20	19%	0.5%	1.05	0.57	0.35
Denmark	Solar PV (residential)	0.01	12%	0.5%	1.53	0.83	0.51
	Solar PV (commercial)	0.10	13%	0.5%	1.02	0.55	0.34
	Solar PV (utility scale)	8	18%	0.5%	0.55	0.30	0.18
France	Solar PV (residential)	0.01	18%	0.5%	1.52	0.82	0.50
	Solar PV (commercial)	0.50	18%	0.5%	0.76	0.41	0.25
	Solar PV (utility scale)	25	24%	0.5%	0.47	0.25	0.15
Hungary	Solar PV (residential)	0.004	15%	0.5%	10.35	8.61	7.38
	Solar PV (commercial)	0.05	14%	0.5%	6.46	5.28	4.48
	Solar PV (commercial)	0.50	14%	0.5%	3.33	2.55	2.08
	Solar PV (utility scale)	20	14%	0.5%	2.67	2.00	1.62
Italy	Solar PV (residential)	0.004	20%	0.5%	10.26	13.30	16.01
	Solar PV (residential)	0.01	17%	0.5%	1.26	0.68	0.42
	Solar PV (commercial)	0.08	20%	0.5%	9.26	12.27	14.88
	Solar PV (commercial)	0.21	17%	0.5%	0.83	0.45	0.28
	Solar PV (commercial)	0.42	20%	0.5%	9.19	12.23	14.85
	Solar PV (utility scale)	0.83	27%	0.5%	2.51	3.14	3.72
Japan	Solar PV (residential)	0.004	12%	0.5%	3.07	1.66	1.02
	Solar PV (utility scale)	2	14%	0.5%	2.26	1.22	0.75
Korea	Solar PV (commercial)	0.10	15%	0.5%	1.30	0.70	0.43
	Solar PV (utility scale)	2.97	15%	0.5%	1.29	0.70	0.43
Netherlands	Solar PV (floating)	8	14%	0.5%	1.94	1.40	1.11
	Solar PV (residential)	0.20	14%	0.5%	1.98	1.43	1.13
	Solar PV (utility scale)	8	14%	0.5%	1.88	1.37	1.09
Norway	Solar PV (commercial)	0.30	10%	0.5%	1.51	0.82	0.50
United States	Solar PV (residential)	0.01	14%	0.5%	1.06	0.57	0.35
	Solar PV (residential)	0.01	21%	0.5%	1.17	0.63	0.39
	Solar PV (commercial)	0.30	13%	0.5%	0.58	0.31	0.19
	Solar PV (commercial)	0.30	20%	0.5%	0.31	0.17	0.10
	Solar PV (utility scale)	100	23%	0.5%	0.20	0.11	0.07
	Solar PV (utility scale)	100	28%	0.5%	0.14	0.08	0.05
	Solar PV (utility scale)	100	36%	0.5%	0.09	0.05	0.03
	Solar thermal (CSP)	100	50%	0.0%	1.60	0.87	0.54
	Solar thermal (CSP)	100	61%	0.0%	1.32	0.72	0.44
Non-OECD countries							
Brazil	Solar PV (utility scale)	25	31%	0.5%	0.60	0.33	0.20
China	Solar PV (utility scale)	20	18%	0.5%	0.48	0.26	0.16
India	Solar PV (utility scale)	35	20%	0.5%	0.29	0.15	0.09

In most countries the operator or owner is responsible for the decommissioning costs.

Financing methods vary from country to country. Among the most common are:

- Prepayment - money is deposited in a separate account to cover decommissioning costs even before the plant begins operation. The funds cannot be withdrawn other than for decommissioning.
- External sinking fund (Nuclear Power Levy) - is built up over the years from a percentage of the electricity rates charged to consumers. Proceeds are placed in a trust fund outside the utility's control.
- Surety fund, letter of credit, or insurance purchased by the utility to guarantee that decommissioning costs will be covered even if the utility defaults.

Many coal-fired power plants are expected to close in coming years. Coal plant communities are faced with potentially long-term job and tax revenue loss, legacy environmental contamination and the need for new economic opportunities.

References:

- *IEA, NEA-OECD "Projected Costs of Generating Electricity. 2020 Edition", 2020*
- *NEA-OECD "The Full Costs of Electricity Provision", NEA No. 7298, 2018*
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Fiche 2.4.1, Cost for system integration – Maneuverability

Fiche – summary of data and considerations

Category for the assessment	Economics
Indicator	2.4 Cost for system integration
Sub-indicator	2.4.1 Maneuverability
Date of release	2023 September 20
Responsible partner	RATEN ICN
Contributing organizations	-
Authors	C.A. Margeanu
Version	1.0

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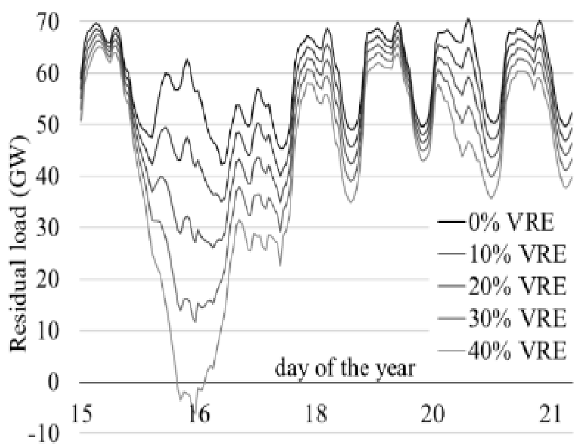
The private costs can be differentiated into "plant-level costs" and "system costs". Plant-level costs are related to electricity generation at the power plant and include: capital costs, fuel costs, non-fuel operation and maintenance (O&M) costs, and carbon emission costs (if a carbon market exists). The "levelized cost of electricity" (LCOE) is widely used to evaluate the costs of various types of electricity producing systems. System costs are all the expenses connected with delivering the power generated at the plant to the areas where it is needed on time and reliably. These expenses include the costs of transmission and distribution networks (*grid costs*), storage technologies, and a variety of auxiliary services necessary for the stable operation of an energy system (*balancing costs*). System costs often include the *profile costs* defined as the additional specific capital and operational costs that electricity generation from a new plant produces in the remaining electricity system, as well as any overproduction costs of electricity generation from variable renewable energy (VRE) sources.

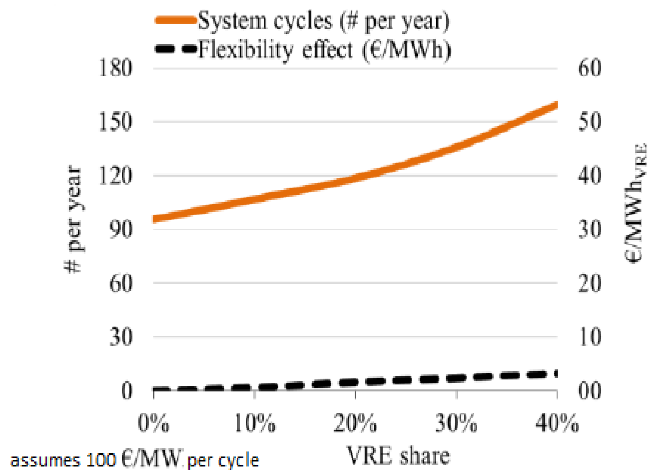
Base load units are usually large nuclear and coal-fired plants which have slow ramp rates and relatively high minimum generation levels (turn-down capability); it can take a long time to start back up once they have been cycled off. Intermediate or peak load plants are generally natural gas or oil-fired plants which have faster ramp rates and relatively lower minimum generation levels; it can be shut down and started up relatively quickly. Hydro power generation has fast response, but can be restricted by environmental constraints (such as erosion control, accommodating fish species, etc.), scheduling practice, and market characteristics. Any additional electricity generation in an operating energy system leads to lower average full load hours of the existing plants, which in turn raises the specific generation costs. However, for base-load and intermediate or peak load plants, these costs do not or no longer appear if or when the old capacities are decommissioned. Therefore, when discussing profile costs the focus is on new VRE power generation. Profile costs are the marginal costs of the temporal variability of VRE output, being reflected in the structure of day-ahead spot prices and materialize as reduced "energy value" of wind and solar power.

Large solar and wind generation ramps happen over several minutes to hours. Using regulation units to compensate for solar ramps is both costly and unnecessary because regulation is more expensive than other services. To integrate higher levels of variable generation technologies such as solar and wind, electricity systems need to ensure that grid operators have access to adequate, flexible sources of generation that can provide the additional load following required by VRE sources.

Thermal gradients of power plants cause ramping and cycling to be costly and ramping constraints require plants to run at part load to be able to follow steep gradients of residual load (load net of VRE generation). This is called *flexibility effect* according to Nicolosi "The Economics of Renewable Electricity Market Integration. An Empirical and Model-Based Analysis of Regulatory Frameworks and their Impacts on the Power Market" (2012). The flexibility effect covers only scheduled ramping and cycling, while uncertainty-related ramping and cycling are reflected in balancing costs.

The figures below illustrate the increasing of residual load ramps with penetration level and the corresponding flexibility effect, highlighted by Hirst's study "Integration costs revisited – An economic framework for wind and solar variability" (2015).





Costs estimates of the flexibility effect are rather scarce and most of these find the cost of hour-to-hour variability to be very small as revealed in the following. An extensive assessment of ramping and cycling costs was published by (NREL, 2013) estimating the cost from 1.0 to 3.2 USD/MWh at 33% penetration level for renewables. Nicolosi (2012) finds the utilization effect to be much larger than the flexibility effect. Increased ramps do not seem to have significant impact on the market value of VRE generators.

The profile costs vary significantly depending on how flexible the entire system is or is projected to be in the future, especially with high penetration rates of VRE technologies. According to various studies, the profile costs of VRE technologies can be drastically reduced by several approaches as follows: consumer demand response (including temporal flexibility in charging electric vehicles), grid and storage capacity extensions, combining wind and solar PV with the use of dispatchable renewable energy technologies, as well as system-friendly design, location or orientation/tilt of wind and solar PV plants. The studies estimates indicating extremely high marginal profile costs for certain VRE shares (over 15% share for solar PV and exceeding 25% share for wind) should be carefully interpreted if no electricity demand able to adjust is assumed or no low-cost supply-side flexibility solutions can be achieved.

<u>References:</u>

- *IEA, NEA-OECD "Projected Costs of Generating Electricity. 2020 Edition", 2020*
- *NEA-OECD "The Full Costs of Electricity Provision", NEA No. 7298, 2018*
- *S. Samadi "The Social Costs of Electricity Generation - Categorising Different Types of Costs and Evaluating Their Respective Relevance", Energies, Vol.10, 2017, www.mdpi.com/journal/energies*
- *M. Nicolosi "The Economics of Renewable Electricity Market Integration. An Empirical and Model-Based Analysis of Regulatory Frameworks and their Impacts on the Power Market", Ph.D. thesis, University of Cologne, 2012*

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- *E. Delarue et al. "Determining the impact of renewable energy on balancing costs, back up costs, grid costs and subsidies", Catholic University Leuven, 2016*
- *NREL "Western Wind and Solar Integration Study Phase 2", National Renewable Energy Laboratory, Golden, USA, 2013*

Fiche 2.4.2, Cost for system integration – Load following

Fiche – summary of data and considerations

Category for the assessment	Economics
Indicator	2.4 Cost for system integration
Sub-indicator	2.4.2 Load following
Date of release	2023 September 20
Responsible partner	RATEN ICN
Contributing organizations	-
Authors	C.A. Margeanu
Version	1.0

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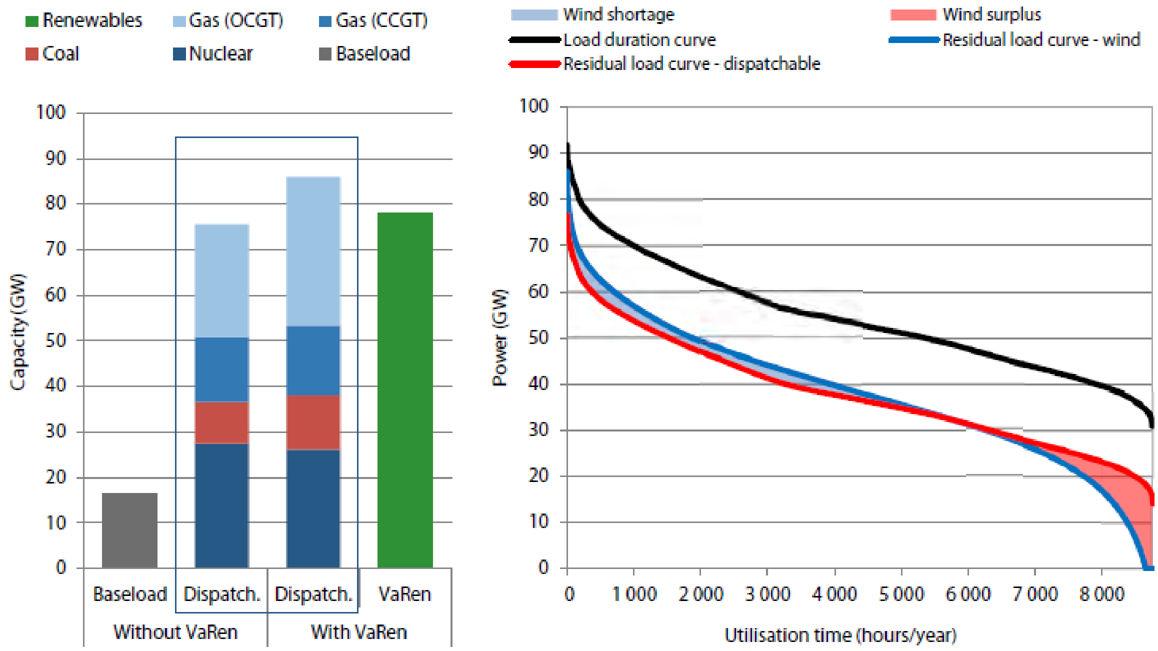
Base load units are usually large nuclear and coal-fired plants which have slow ramp rates and relatively high minimum generation levels (turn-down capability); it can take a long time to start back up once they have been cycled off. Intermediate or peak load plants are generally natural gas or oil-fired plants which have faster ramp rates and relatively lower minimum generation levels; it can be shut down and started up relatively quickly. Hydro power generation has fast response, but can be restricted by environmental constraints (such as erosion control, accommodating fish species, etc.), scheduling practice, and market characteristics. Any additional electricity generation in an operating energy system leads to lower average full load hours of the existing plants, which in turn raises the specific generation costs. However, for base-load and intermediate or peak load plants, these costs do not or no longer appear if or when the old capacities are decommissioned. Therefore, when discussing profile costs the focus is on new VRE power generation. Profile costs are the marginal costs of the temporal variability of VRE output, being reflected in the structure of day-ahead spot prices and materialize as reduced "energy value" of wind and solar power.

Utilization costs (or profile costs) refer to the increase in power system costs due to the variability of VRE production. They reflect the fact that in a system with VRE, providing the residual load is typically more expensive than in a system with a dispatchable technology but with an identical LCOE (levelised cost of electricity).

Long-term changes in the structure of the conventional generating mix induced by the deployment of VREs include the need for a larger overall capacity and a shift from base-load technologies towards intermediate and peak-load capacity. In term of electricity generated, the share of base-load generation reduces and is replaced by intermediate and peak-load plants. This effect is illustrated in the figure below, where a comparison between the residual load curves for a system with a given VRE capacity (wind at 30% share in blue) and a system where the same amount of energy is provided by base-load capacity (30% of demand, in red), according to NEA study "Full costs of Electricity Provision" (2018).



The literature provides several estimates of utilization costs, suggesting that these costs are significant, especially for energy systems with high VRE penetration levels. NEA and IEA estimates for wind power using a model based on residual load duration curve are quite similar lying between 4 and 10 USD/MWh at 10% and 30% penetration levels (IEA, 2014 and NEA, 2012). The estimates for solar PV at the same 10% and 30% levels of penetration are within a wider range, as follows: IEA estimates are between 4 and 15 USD/MWh, while NEA's findings vary from 13 to 26 USD/MWh.

According to a broad survey of about 30 studies on utilization costs, long-term utilization costs for wind at a 30% penetration level range between 15 and 25 EUR/MWh (Hirth, 2013). If the average electricity price is about 70 EUR/MWh, integration costs may be in the range of 25–35 EUR/MWh at a penetration rate of 30–40% in thermal power systems. In other words, integration costs increase direct generation costs by 35-50%.

By assuming a combined solar PV and wind penetration rate ranging from 19% to 35%, the Catholic University of Leuven (Delarue et al., 2016) estimated utilization costs between 3.3 and 8.4 EUR/MWh for Belgium and from 6.5 to 12.6 EUR/MWh for Central Western Europe.

References:

- *IEA, NEA-OECD "Projected Costs of Generating Electricity. 2020 Edition", 2020*
- *NEA-OECD "The Full Costs of Electricity Provision", NEA No. 7298, 2018*
- *S. Samadi "The Social Costs of Electricity Generation - Categorising Different Types of Costs and Evaluating Their Respective Relevance", Energies, Vol.10, 2017, www.mdpi.com/journal/energies*

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- *L. Hirth et al. "Integration costs revisited – An economic framework for wind and solar variability", Renew. Energy, Vol. 74, 2015*
- *L. Hirth "The market value of variable renewables: The effect of solar wind power variability on their relative price", Energy Economics, Vol. 38, 2013.*
- *E. Delarue et al. "Determining the impact of renewable energy on balancing costs, back up costs, grid costs and subsidies", Catholic University Leuven, 2016*

Fiche 2.4.3, Cost for system integration – Stability

Fiche – summary of data and considerations

Category for the assessment	Economics
Indicator	2.4 Cost for system integration
Sub-indicator	2.4.3 Stability
Date of release	2023 September 20
Responsible partner	RATEN ICN
Contributing organizations	-
Authors	C.A. Margeanu
Version	1.0

The cost to society of generating electricity using various technologies, usually referred to social cost, are composed by private costs and external costs. The private costs of a good are considered by the producer when determining production volume, the goal being to minimize these costs. External costs are human activity expenses not accounted for by the market participant creating the externality.

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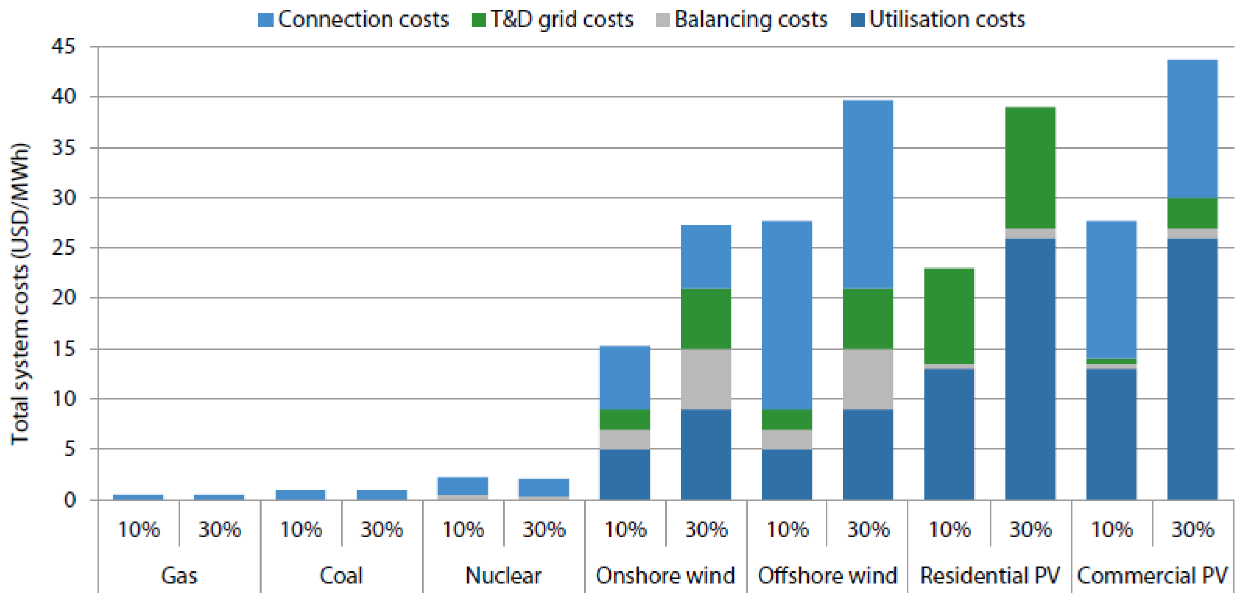
The figure below illustrates the system cost of different generation technologies, according to NEA's study "Full costs of Electricity Provision" (2018).



The stable operation of an electricity system requires electricity demand and electricity supply to be always equal. As a result, electrical networks require a central system operator to ensure that unexpected (and hence unpredictable) short-term changes in both energy demand and supply may be compensated for by contracting sufficient reserves in advance. These reserves are utilized to supply balancing power if necessary.

The need to retain such reserves has financial consequences since it necessitates more capacity than a hypothetical system in which demand and supply are completely predictable and any type of system failure can be ruled out. As plant efficiency is often worse when a plant is operating below its full capacity and/or needs to ramp up and down regularly to provide reserve capacity, additional fuel expenditures (and the associated emissions costs) also accumulate. Additionally, frequent ramping may also negatively affect a plant's reliability and reduce its lifetime.

Both planned and unplanned outages can occur during operation of power plants regardless of the type of technology used for energy generation, therefore balancing costs can be attributed to all types of power plants to a certain extent. When VRE sources are used to produce energy, as in the case of wind and solar PV power plants, the balancing costs are typically higher. Power generation from renewable sources is significantly more variable, less predictable and less controllable than power generation from other sources, therefore VRES requires other power plants in the system to modify their output more often and/or more quickly in order to maintain the balance between supply and demand.

In the table below, the specific balancing costs of different electricity generation technologies at varying penetration rates are provided according to Samadi's review study "The Social Costs of Electricity Generation - Categorizing Different Types of Costs and Evaluating Their Respective Relevance" (2017).

Country or Region	Technology	Penetration Rate (Share of Total Electricity Generation)	Balancing Costs (in €-cent/kWh)	Comment
Six OECD countries	Nuclear	10%	<0.1	-
		30%	<0.1	
	Wind (onshore and offshore) and solar PV	10%	0.3	Median; full range: 0.2–0.7 (NEA, 2012)
		30%	0.5	Median; full range: 0.5–1.3
Arizona, USA	Solar PV	8%	0.2	Median, full range: 0.2–0.3 (T. Mason et al, 2012)
USA and several European countries	Wind (onshore and offshore)	≈10%	0.3	Median; full range: <0.1–0.4
		≈20%	0.3	Median; full range: <0.1–0.5 (H. Holttinen et al,2013)
		≈30%	0.4	Median; full range: 0.1-–0.6
Eleven European countries	Solar PV	15%	0.1	- (D. Pudjianto et al., 2013)
Several European countries and several regions of the USA	Wind (onshore and offshore)	≈1% to 40%	≈0.3	(L. Hirth et al., 2015) Median, full range: <0.1–1.3 No clear correlation between specific balancing costs and penetration level

In thermal-based systems, the balancing costs are estimated in the range of 2 to 6 EUR/MWh (L. Hirth et al., 2015 and H. Holttinen et al., 2013), while these costs are significantly lower (less than 1 EUR/MWh) in systems with high hydro capacity.

The Catholic University of Leuven has assessed balancing costs in Belgium and Central Western Europe (CWE) for different VRE penetration levels (from 19% to 35% of solar PV and wind energy). Estimates of balancing costs lie in a range of 2.1 and 4.7 EUR/MWh in Belgium and between 1.4 and 3.6 EUR/MWh in CWE (Delarue et al., 2016).

Despite being a dispatchable technology, whose output is predictable, some balancing costs must also be attributed to nuclear energy. These costs, which are below EUR 1 EUR/MWh, are explained by the fact that nuclear power plants constitute the installations with the largest capacity. Smaller reactors would further reduce nuclear energy's balancing costs.

The most recent estimates for balancing costs (according NEA -OECD study "The Full Costs of Electricity Provision", 2018) lie in a range of 2 to 6 EUR/MWh for wind power in thermal systems, while costs for solar PV, wind power in hydro-based systems or nuclear are much lower, less than 1 EUR/MWh.

<u>References:</u>

- *IEA, NEA-OECD "Projected Costs of Generating Electricity. 2020 Edition", 2020*
- *NEA-OECD "The Full Costs of Electricity Provision", NEA No. 7298, 2018*
- *S. Samadi "The Social Costs of Electricity Generation - Categorising Different Types of Costs and Evaluating Their Respective Relevance", Energies, Vol.10, 2017, www.mdpi.com/journal/energies*
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- *E. Delarue et al. "Determining the impact of renewable energy on balancing costs, back up costs, grid costs and subsidies", Catholic University Leuven, 2016*

Fiche 2.4.4, Cost for system integration – Easy to be integrated in local/regional grids

Fiche – summary of data and considerations

Category for the assessment	Economics
Indicator	2.4 Cost for system integration
Sub-indicator	2.4.4 Easy to be integrated in local/regional grids
Date of release	2023 September 20
Responsible partner	RATEN ICN
Contributing organizations	-
Authors	C.A. Margeanu
Version	1.0

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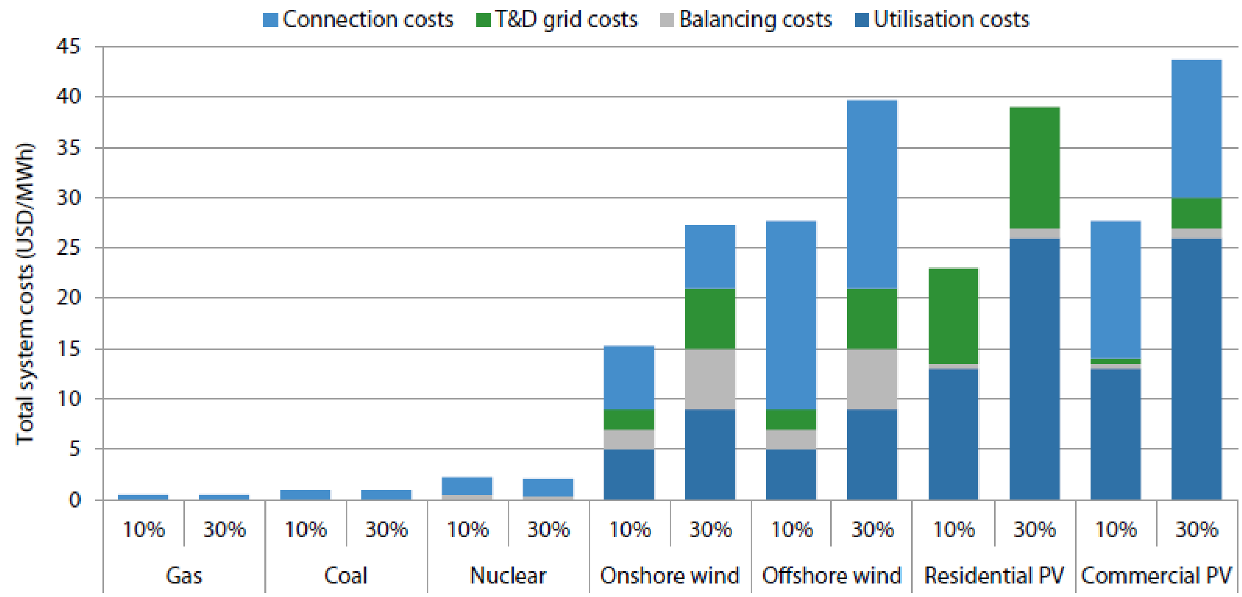
The private costs can be differentiated into "plant-level costs" and "system costs". ***Plant-level costs*** are related to electricity generation at the power plant and include: capital costs, fuel costs, non-fuel operation and maintenance (O&M) costs, and carbon emission costs (if a carbon market exists). The "levelized cost of electricity" (LCOE) is widely used to evaluate the costs of various types of electricity producing systems. ***System costs*** are all the expenses connected with delivering the power generated at the plant to the areas where it is needed on time and reliably. These expenses include the costs of transmission and distribution networks (*grid costs*), storage technologies, and a variety of auxiliary services necessary for the stable operation of an energy system (*balancing costs*). System costs often include the *profile costs* defined as the additional specific capital and operational costs that electricity generation from a new plant produces in the remaining electricity system, as well as any overproduction costs of electricity generation from variable renewable energy (VRE) sources.

The figure below illustrates the system cost of different generation technologies, according to NEA's study "Full costs of Electricity Provision" (2018).

The specific *grid costs* of a new power plant are difficult to establish precisely and may vary considerably due to several factors such as: the proximity of a new plant to the current transmission grid, its distance from demand centers, its capacity factor, the extent and quality of the existing grid, and the lifetime of transmission investments. In recent years, research on grid reinforcement and extension costs has concentrated on expenses related with increased usage of renewable energy sources.



In the table below, the specific grid costs of different electricity generation technologies at varying penetration rates are provided according to Samadi's review study "The Social Costs of Electricity Generation - Categorising Different Types of Costs and Evaluating Their Respective Relevance" (2017).

Country or Region	Technology	Penetration Rate (Share of Total Electricity Generation)	Grid Costs (€-cent/kWh)	Comments
USA	Wind (onshore and offshore)	Not provided (varying)	1.4	Median; full range: 0–7.2 (A. Mills et al., 2012)
Six European countries	Wind (onshore and offshore)	≈10%–60%	≈0.4	Median; full range: ≈ 0.2–1.1 (IEA collaboration, 2011) Original data in €/kW; conversion assumes 2000 full load hours per year, 7% discount rate and 40 years grid lifetime No clear correlation between specific grid costs and penetration level
Six OECD countries	Wind (onshore)	10% 30%	0.2 0.3	Median; full range: < 0.1–0.3 Median; full range: 0.2–2.0
	Wind (offshore)	10% 30%	0.1 0.2	Median; full range: < 0.1–0.2 Median; full range: < 0.1–1.1 (NEA, 2012)
	Solar PV	10% 30%	0.4 0.5	Median; full range: < 0.1–0.5 Median; full range: 0.2–4.3
	Nuclear, coal, gas	10% and 30%	0	-
Eleven European countries	Solar PV	15% to 18%	1.2	Maximum; lower in some countries; only distribution grid and cross-country transmission lines taken into account (D. Pudjianto et al., 2013)
Australia	CSP (with storage) Geothermal Biomass Coal CCS	18%–23%	0.2 0.3 <0.1 <0.1	Concentrating solar thermal power - (W. Hou, 2014)

Costs from several European countries show an average value of 7 EUR/MWh, with large differences between the analyzed countries (KEMA, 2014). Grid costs for Belgium, for VRE penetration levels between 19% and 35%, were estimated at 3 EUR/MWh (Delarue et al., 2016). The PV Parity Project estimated that additional transmission costs would be 0.5 EUR/MWh in 2020, rising to 3 EUR/MWh by 2030 as penetration increases. Reinforcing the distribution network to accommodate more dispersed PV resources will cost around 9 EUR/MWh by 2030 (D. Pudjianto et al., 2013).

The quantitative estimates of grid costs available are characterized by substantial variations, reflecting the features of each individual system, different penetration levels considered, and whether distribution costs have been included, as well as certain methodological assumptions. However, published estimates range from a few USD/MWh to 10 to 20 EUR/MWh.

References:

- *IEA, NEA-OECD "Projected Costs of Generating Electricity. 2020 Edition", 2020*
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Fiche 2.4.5, Cost for system integration – Realistic solution for large scale storage

Fiche – summary of data and considerations

Category for the assessment	Economics
Indicator	2.4 Cost for system integration
Sub-indicator	2.4.5 Realistic solution for large scale storage
Date of release	2023 September 20
Responsible partner	RATEN ICN
Contributing organizations	-
Authors	C.A. Margeanu
Version	1.0

The fast expansion of intermittent renewable energy generation, particularly wind and solar, in many regions of the world has created a significant incentive to build large-scale energy storage for electricity. Due to the growing annual share (desired or imposed) of electricity from renewable technologies having naturally-fluctuating power flows (like solar PV and wind) and relatively low load factors, the combined installed capacities of those technologies are expected to become much larger than conventional electrical peak power demand.

The ability of such intermittent renewable sources to replace dispatchable sources, taking surplus power sometimes, and bridging intermittent gaps will depend on how much electricity storage can be produced. There are questions of scale – power and energy capacity. Some stored energy usually needs to be available as electricity over days and weeks, but also for short-term storage over minutes and hours. To evaluate different electrical storage systems in a range of applications and services, both value and cost must be accurately determined.

Electricity cannot itself be stored on any scale, but it can be converted to other forms of energy which can be stored and later reconverted to electricity on demand. Storage systems for electricity include battery, flywheel, compressed air, and pumped hydro storage. Any systems are limited in the total amount of energy they can store. Their energy capacity is expressed in megawatt-hours (MWh), and the power, or maximum output at a given time, is expressed in megawatts of electric power (MW or MWe). Electricity storage systems may be designed to provide ancillary services to a transmission system including frequency control.

Very effective storage of energy is achieved in fossil fuels and nuclear fuel, before electricity is generated from them.

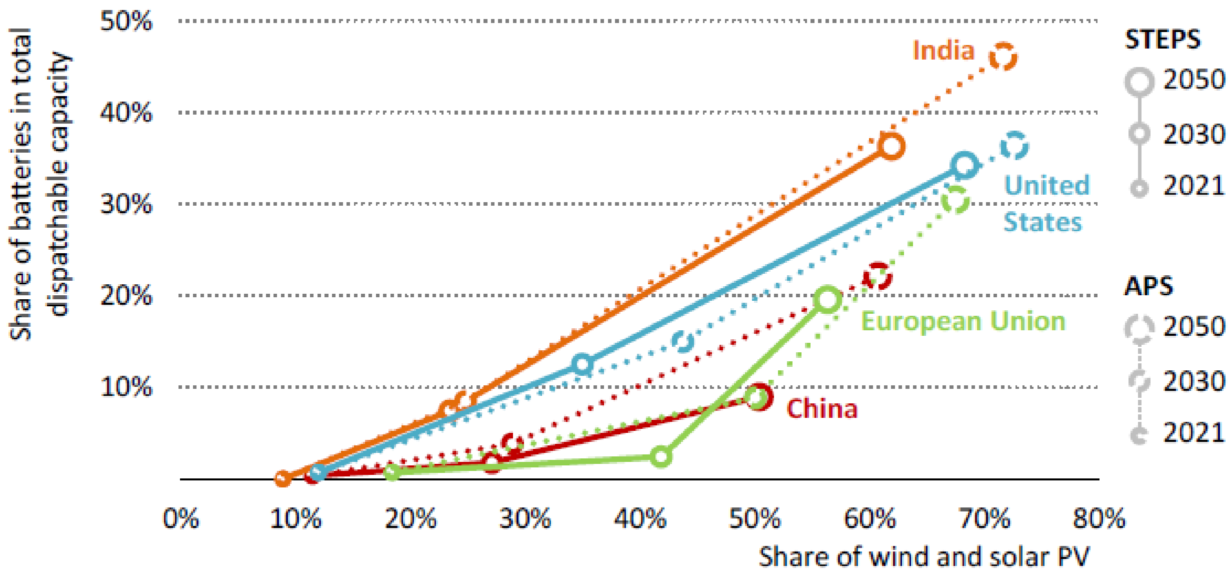
Pumped storage involves pumping water uphill to a reservoir from which it can be released on demand to generate hydroelectricity, with about 70% efficiency of the double process. Pumped storage is long-term if required; it accounted for 95% of the world's large-scale electricity storage in mid-2016, and 72% of the storage capacity added in 2014.

However, battery storage is becoming increasingly popular. In 2021, more than 6 GW of grid-scale battery storage was added, reaching about 16 GW connected to electricity networks, according to IEA. Building-scale power storage emerged in 2014 and has grown by 50% year-on-year, mainly based on lithium-ion batteries. In 2015 battery storage costs were around 400 USD/kWh of contained energy, and 1.6 GW was installed or planned. The cost dropped to 141 USD/kWh in 2021 and reached 151 USD/kWh in 2022, according to Bloomberg NEF's annual battery price survey.

Battery storage is projected to be the fastest growing source of power system flexibility in all scenarios over the outlook period according to the IEA study “World Energy Outlook 2022”. Battery systems are modular, allowing their deployment and scale up rapidly in almost any location. Utility-scale batteries can provide crucial system functions in addition to energy storage, such as assisting with the restoration of grid operations during a black-out, maintaining short-term balancing, or providing operating reserves. Their provision of localized flexibility may also reduce the need for investment in new transmission and distribution infrastructure.

The figure below illustrates the share of batteries in total dispatchable capacity and share of variable renewables in electricity generation for several selected regions considering STEP (Stated Policies Scenario) and APS (Announced Pledges Scenario) scenario and time period 2021-2050, according to the IEA study “World Energy Outlook 2022”.

Battery storage capacity rises in tandem with the share of wind and solar PV, helping to provide flexibility and security for power systems. This highlights its role as an important source of additional flexibility as renewables are scaled up and traditional providers of flexibility such as coal-fired power plants are retired.



IEA study “World Energy Outlook 2022” identify lithium-ion batteries as the fastest growing storage technology in the world. In the NZE (Net Zero Emissions by 2050) Scenario, battery storage capacity is projected to reach 778 GW by 2030 and 3860 GW by 2050, from 27 GW in 2021.

Energy storage with compressed air (CAES) in geological caverns or disused mines is being tested as a relatively large-scale storage technology, using gas-fired or electric compressors, the adiabatic heat being dumped (this being the diabatic system). When released (with preheating to compensate for adiabatic cooling) it powers a gas turbine with additional fuel burn, the exhaust being used for preheating. CAES installations can be up to 300 MW, with overall about 70% efficiency. CAES capacity can even out the production from a wind farm or 5-10 MW of solar PV capacity and make it partly dispatchable. Two diabatic CAES systems are in operation, in Alabama (110 MW, 2860 MWh) and Germany (290 MW, 580 MWh). Batteries have better efficiency than CAES (output as proportion of input electricity) but they cost more per unit of capacity, and CAES systems can be much larger.

The cryogenic storage works by cooling air down to -196°C, at which point it turns to liquid for storage in insulated low-pressure tanks. Exposure to ambient temperatures causes rapid re-gasification and 700-fold expansion in volume, used to drive a turbine, and create electricity without combustion. Energy can be stored for weeks (instead of hours as for batteries) at a projected levelized cost of 110 £/MWh (142 USD/MWh) for a 10-hour, 200 MW/2 GWh system.

References:

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- *IEA, NEA-OECD "Projected Costs of Generating Electricity. 2020 Edition", 2020*

NEA-OECD "The Full Costs of Electricity Provision", NEA No. 7298, 2018

Fiche 2.5, External costs

Fiche – summary of data and considerations

Category for the assessment	Economics
Indicator	2.5 External costs
Sub-indicator	-
Date of release	2023 September 20
Responsible partner	RATEN ICN
Contributing organizations	-
Authors	C.A. Margeanu
Version	1.0

The implicit subsidies that allow waste products of energy consumption to be thrown into the biosphere outweigh any direct subsidies. The largest of them are associated to fossil fuel producers. Nuclear energy has always had to pay for its own waste management and disposal (about 5% of the cost of generating, plus a comparable price for decommissioning). Renewable energy sources produce wastes during energy generation; they can occasionally be unpleasant or even severely hazardous, but are handled in the same way as conventional industrial risks and wastes. New wind turbines are frequently installed on the same location as decommissioned ones. When a solar PV panel reaches the end of its useful life, it becomes electronic waste.

External costs are those incurred regarding health and the environment, are quantifiable, but are not included into the cost of power and hence must be borne by society. They are especially concerned with the consequences of air pollution on human health, crop yields, and structures, as well as occupational sickness and accidents. The impact of global warming is now widely acknowledged.

External expenses should be considered and, if feasible, quantified to help with cost-benefit analysis, technology comparison, and life cycle analysis.

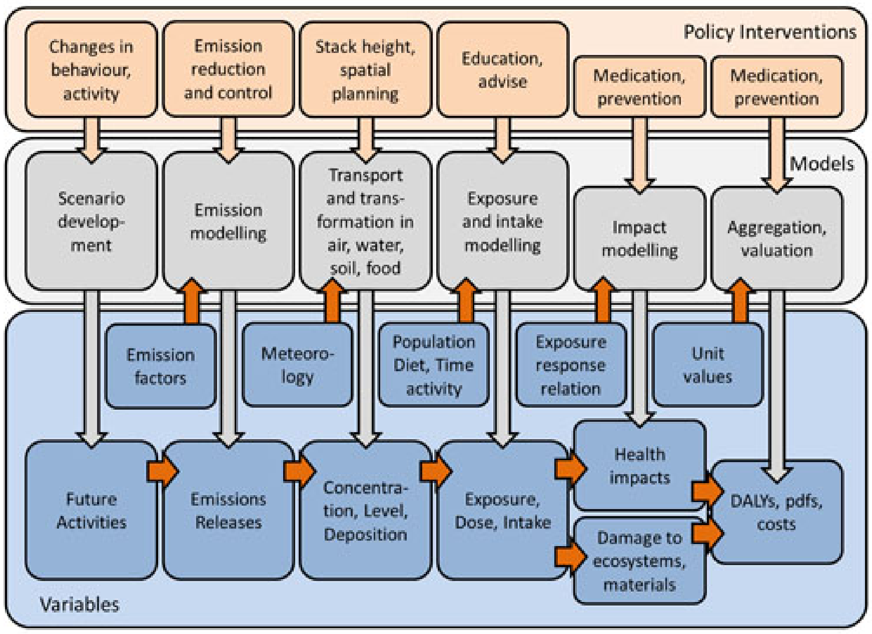
The report of ExternE (acronym for External Cost of Energy) , a major European study of the external costs of various fuel cycles, focusing on coal and nuclear, was released in 2001 and further figures have emerged since. Following 2005, several further projects used and improved the tools in order to achieve a more "Integrated Assessments".

"ExternE-Methodology" is an approach to determine environmental external costs; it was established during the "ExternE project-series" and is known as the Impact-Pathway-Approach. The EcoSense model now includes a tool and data for assessing environmental external costs using the Impact-Pathway-Approach. The basic principles of the methodology are as follows:

1. The assessment or weighing of consequences is carried out as quantitatively as feasible based on the fact that only quantitative algorithms offer the essential transparency and repeatability of outcomes.
2. A monetary unit is the common unit into which effects are converted, leading to several advantages: units are possible, monetary values may be transferred from one application to another, and in order to compare costs and benefits, benefits must be converted into monetary units. External impacts must be expressed in monetary units in order to be internalized through taxes.
3. Impacts are assessed based on the (measured) preferences of the affected well-informed population.

4. In order to get relevant findings, the interviewees must comprehend the change in utility that happens as a result of the effect to be examined. This means that it is critical to value a damage rather than a pressure or effect.
5. As a result, the approach should be able to determine site and time dependent external costs. Only a detailed bottom-up calculation allows a close appreciation of site, time, and technology dependence. Thus, the so-called 'Impact pathway approach' is applied for most environmental impacts.

Impact pathway approach is a bottom-up technique in which environmental benefits and costs are calculated by tracing the pathway from source emissions to physical consequences (via quality changes in air, soil, and water), which are then reflected in monetary benefits and costs. The figure below depicts the major phases of the impact pathway approach applied to the effects of pollution emissions.



The methodology used by the ExternE Project of the European Commission (DGXI1) JOULE Programme for assessment of the external costs of energy was applied to nuclear, fossil (coal, lignite, gas, oil) and renewable (wind, solar PV, hydro) fuel cycles. The location of fuel cycle activities, the technologies used, and the type and supply of fuel have all been taken into consideration.

A wide variety of impacts have been considered, including: effects of air pollution on the natural and human environment (materials, crops, forests, freshwater fisheries, etc), consequences of accidents in the workplace, impacts of noise and visual intrusion on amenity, and effects of climate change arising from the release of greenhouse gases. Effects on ecosystems and the impact of global warming were also included despite the high range of uncertainty in adequately quantifying and evaluating them economically. Exposure-response models lead to evaluating the physical impacts in monetary terms.

According to the analysis, nuclear energy costs around one-tenth of what coal does in monetary terms. Nuclear energy costs less than 0.4-euro cents/kWh (0.2-0.7), less than hydro, coal costs more than 4.0 cents/kWh (2-10 cents/kWh in different countries), gas costs 1-4 cents/kWh, and only wind costs less than nuclear, at 0.05-0.25 cents/kWh on average.

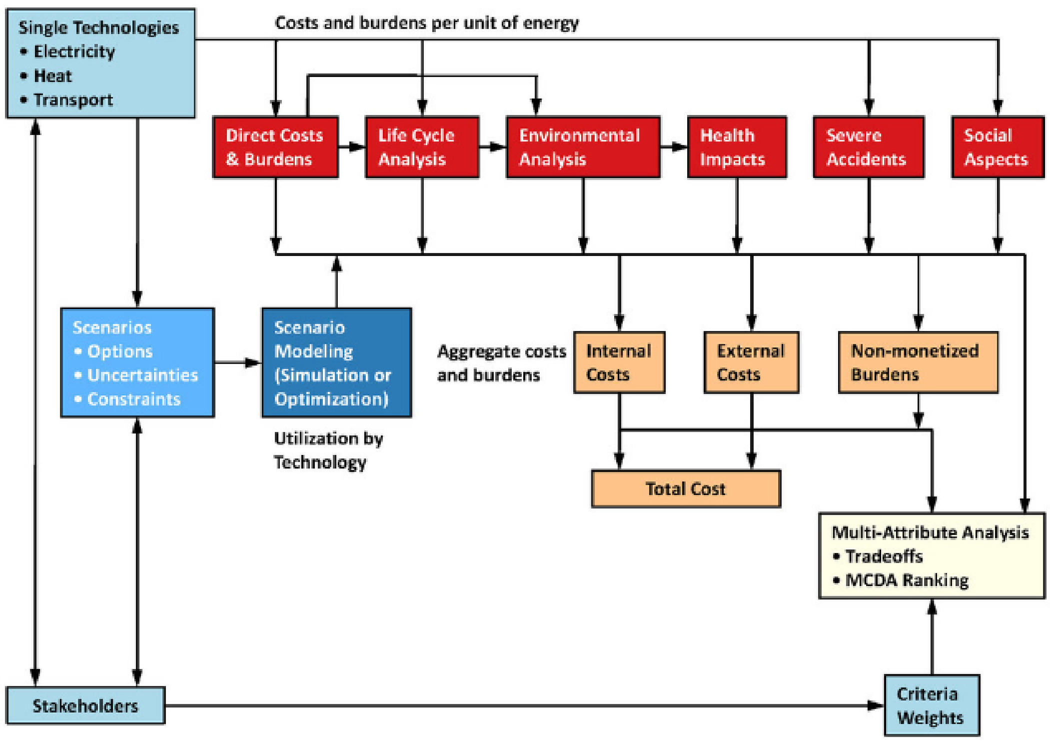
Without these external expenditures, the cost of power generation in the EU is around 4 cents/kWh. If these external expenses were factored in, the EU price of coal-fired energy would more than double, while gas-fired electricity would rise by roughly 30%.

The table below shows the external costs provided by four important studies dealing with the externalities assessment, presented by Burtraw et al. (2012) in "The True Cost of Electric Power: An Inventory of Methodologies to Support Future Decision making in Comparing the Cost and Competitiveness of Electricity Generation Technologies", and included in NEA's study "Full costs of Electricity Provision" (2018).

Study	Estimates of external costs (Mills/kWh or USD/MWh)								
	Coal	Peat	Oil	Gas	Nuclear	Biomass	Hydro	PV	Wind
ORNL/RFF	2.3	–	0.35-2.11	0.35	0.53	3	–	–	–
Rowe et al.	1.3-4.1	–	2.2	0.33	0.18	4.8	–	–	0.02
EC ExternE	27-202	27-67	40.3-148	13.4-53.8	3.4-9.4	0-67	0-13	8.1	0-3.4
NRC	2-126	–	–	0.01-5.78	–	–	–	–	–

* A mill is one-tenth of a cent or one-thousandth of a dollar; PV is photovoltaic.

The Paul Scherrer Institut conducted a European study of production and external costs, specifically for power generation in Switzerland (the GaBE Project), and found that the damage costs from fossil fuels are 10% to 350% of the production costs, whereas those from nuclear are relatively minimal. The analytical framework for comprehensive technology assessment is illustrated in the figure below.



Consideration of external costs leads to the conclusion that the public health benefits associated with reducing greenhouse gas emissions from fossil fuel burning could be the strongest reason for pursuing them. Adoption of any policies or conventions that take into consideration the external costs of generating electricity would have a significant positive impact on the possibilities for a major rebirth of nuclear energy.

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  - *vol.5 Nuclear, EUR16524, 1995*
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- *EC "Externalities of Energy. Methodology 2005 update", ExternE project website, EUR21951, 2005 https://www.ier.uni-stuttgart.de/en/research/projects/externe/*
- *D. Burtraw, A. Krupnick, G. Sampson "The True Cost of Electric Power: An Inventory of Methodologies to Support Future Decision making in Comparing the Cost and Competitiveness of Electricity Generation Technologies", Resources for the Future, Washington, DC, www.rff.org/files/sharepoint/WorkImages/Download/RFF-Rpt-BurtrawKrupnick%20TrueCosts.pdf, 2012.*
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IEA "World Energy Outlook 2022", 2022

Fiche 2.6, LCOE

Fiche – summary of data and considerations

Category for the assessment	Economics
Indicator	2.6 LCOE
Sub-indicator	-
Date of release	2023 September 20
Responsible partner	RATEN ICN
Contributing organizations	-
Authors	C.A. Margeanu
Version	1.0

Levelized cost of electricity (LCOE) is the costs per unit of electricity generated, defined as the ratio of total lifetime expenses and the total expected output, expressed in terms of present value equivalent.

Different modelling approaches can be used to estimating LCOE values. For example, all cost and revenues can be expressed in constant money (e.g. US dollars) without inflation. Another approach is to take inflation into account using so-called current money. Deciding whether to include inflation will affect the discount rate used in the calculation. One can also include changes in estimated real costs as a function of time or use values that are time independent.

LCOE can be also expressed as the average price that would have to be paid by consumers for electricity delivered at the plant "gate" to repay exactly all costs incurred by the owner/operator of a plant, at the selected discount rate, r, in a defined time frame (lifetime of the plant) and without profits. Plant-level costs imply that for the LCOE calculation the overall system effects are not taken into account, i.e. the impact of a power plant on the electricity system as a whole. The system effects, however, can potentially have a significant impact. In the case of variable renewable energies for example, they might negatively impact expected revenues at higher shares of penetration.

The main drivers for the costs of generating electricity are typically *the construction*, *fuel (including expenses for emissions such as CO2, particulates, NOx, and SOx)* as well as *operation and maintenance costs*. These factors are influenced by the size of the individual units, with economies of scale typically reducing costs at larger scale. LCOE of different electricity generation technologies vary significantly depending on the country, the technology and the properties of individual plants.

$$LCOE = \frac{\sum_{t=t_{start}}^{t_{end}} \frac{\left(CapInv_t + O\&M_t + Fuel_t\right)}{(1+r)^t}}{\sum_{t=t_{start}}^{t_{end}} \frac{P_t \cdot 8760 \cdot Lf_t}{(1+r)^t}} = LUAC + LUOM + LUFC$$

[mill$/kWh] or [$/MWh]

$CapINV_t$ = total capital construction costs in year t;
$O\&M_t$ = operation and maintenance costs in year t;
$Fuel_t$ = fuel costs in year t;
P_t = net electric power of the plant in year t;
t_{start} = beginning of project (start of construction) ;
8760 = number of hours in a year = 24x(31x7+30x4+28)

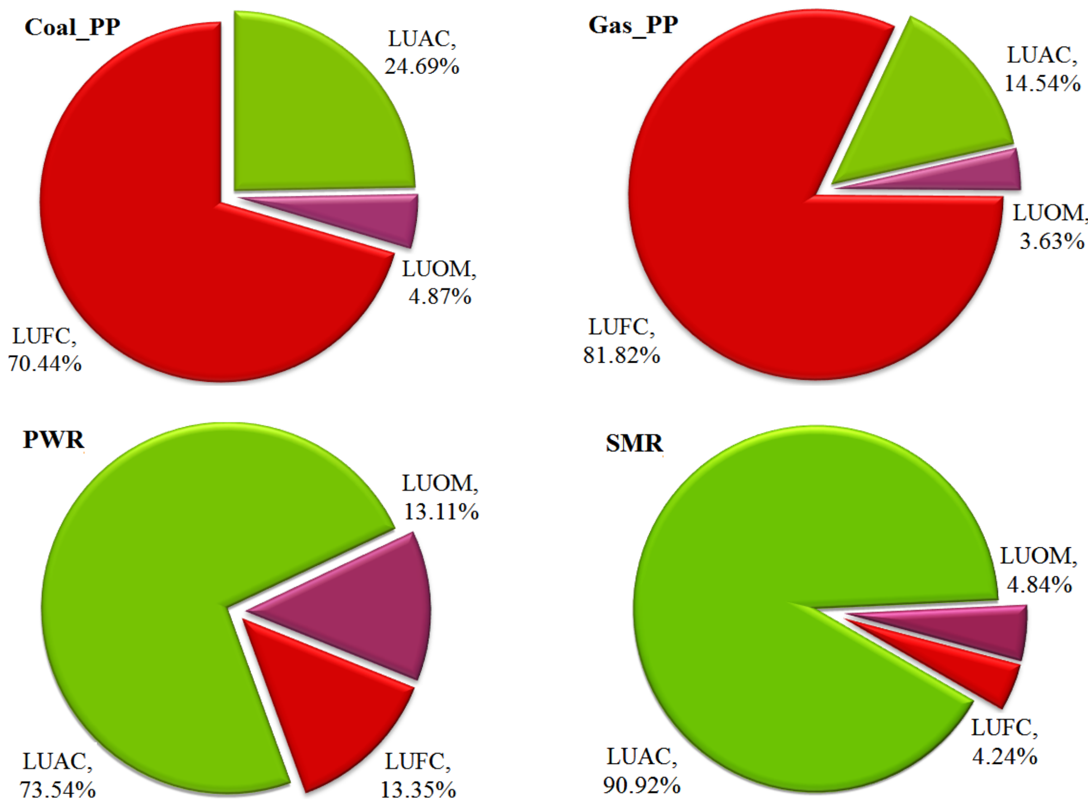
LUAC = levelized capital (amortization) cost;
LUOM = levelized O&M cost;
LUFC = levelized fuel cost;
Lf_t = load factor of the plant in year t;
t_{end} =end of project (lifetime of the plant);

r = discount rate (It takes time value of money into account, i.e. money earned in future has less value than received today. The value is linked to the interest that an investor has to pay for long term bonds.)

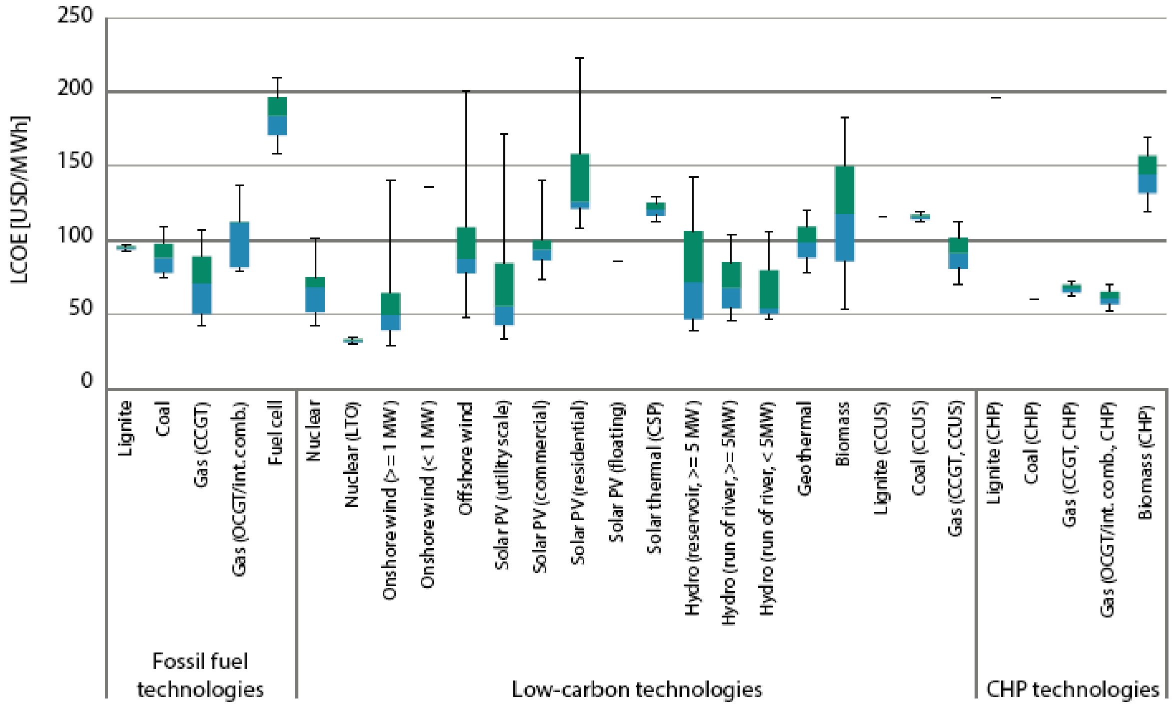
The total capital construction costs represent the investment costs and consist of overnight costs plus financing costs (e.g. interest during construction). The decommissioning and waste management costs are usually included in the investment costs. Similarly, the backfitting costs, composed by all the major refurbishment costs not included in the annual O&M costs and required to keep the performance of the plant within declared values, are taken into consideration in the investment costs.

O&M costs are usually divided into fixed O&M costs, including those that do not depend on the energy generated each year, and variable O&M costs, including those that depend on the energy generated. Usually variable O&M costs are proportional to the annual electricity output.

The contribution of each levelised cost component (LUAC, LUOM, and LUFC) to LCOE is significantly different for various generating technologies. In the figures below, this important aspect is illustrated based on calculation performed with the IAEA's NEST (NESA economic support tool), recommended to be used by Member States to evaluate economic parameters for power plants.



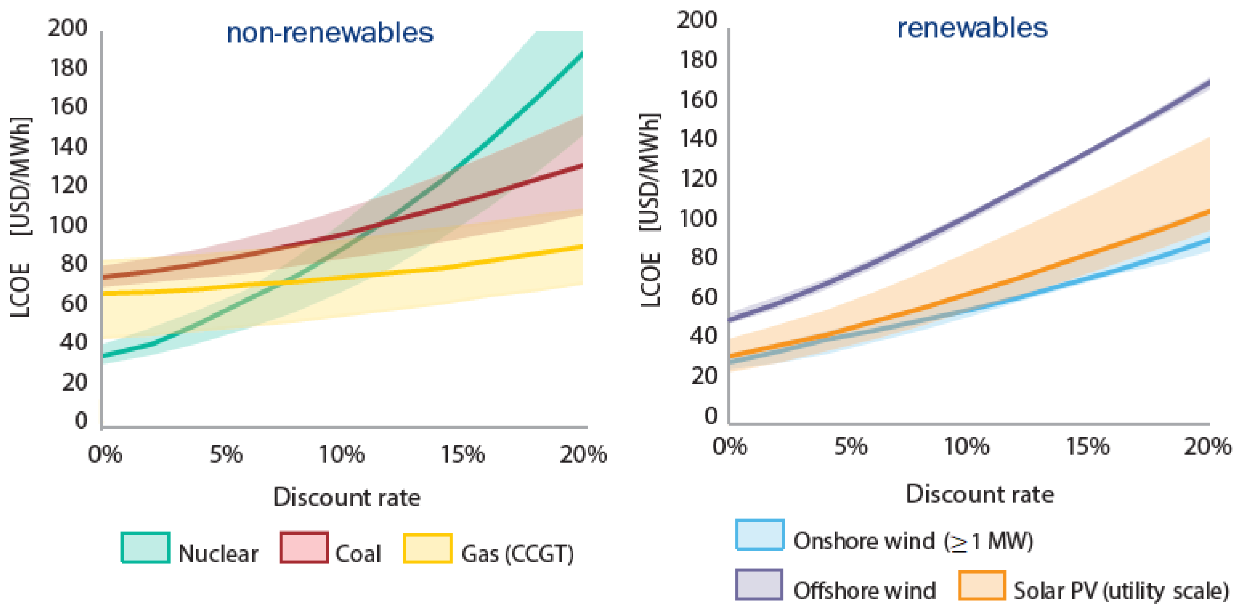
In the figure below, technological options for generating electricity and associated LCOE values are illustrated, according to the IEA and NEA-OECD joint study "Projected Costs of Generating Electricity. 2020 Edition". A discount rate of 7% was considered in LCOE calculations.



Aspects of LCOE costs such as construction, refurbishment and decommissioning expenses are significantly affected by the discount rate. The capital-intensive technologies are more sensitive to changes in the discount rate. The discount rate itself might also be influenced by how capital-intensive a technology is: a technology with relatively high upfront costs might be more exposed to market risks, which increases financing costs.

The impact of the discount rate on LCOE value for several electricity generating technologies analyzed in the IEA and NEA-OECD joint study "Projected Costs of Generating Electricity. 2020 Edition" is illustrated in the figures below. The discount rate varied between 0% to 20%.

LCOE is the principal tool for comparing the plant-level unit costs of different types of generating technologies with different cost components over their operating lifetimes. The LCOE indicates the economic costs of a generic technology, not the financial costs of a specific projects in a specific market. A technology's true economic cost will depend also on its overall share and technical characteristics as well as on the costs and technical characteristics of all other technologies in the system rather than only on the discounted sum of its investment costs and variable costs at the plant-level.



Note: Lines indicate median values, areas the 50% (20% for renewables) central region.

References:

- *IEA, NEA-OECD "Projected Costs of Generating Electricity. 2020 Edition", 2020*
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Fiche 2.7, Macro-economic impact

Fiche – summary of data and considerations

Category of LCA assessment	Economic
Indicator	2.7 Macro-economic impact
Sub-indicator	-
Date of release	2023 September 19
Responsible partner	RATEN ICN
Contributing organizations	-
Authors	M. Constantin
Version	1.0

The following elements and considerations are compiled from (IRENA, 2016), (Americo, 2023), IEA (2021).

Macro-economic impact refers to the overall effects that energy technologies have on a national or the global economy. Generally, the development of new energy technologies may stimulate the economic growth, investment, infrastructure development, job creation, etc. By reducing the dependence on fossil fuel and on the imported resources, a reduction of the economic vulnerabilities may occur. A clean energy can produce economic benefits in terms of avoided healthcare costs, increased agricultural productivity, and reduced damage from extreme weather events. Energy technologies with reduced cost of energy can lower energy bills for households and businesses creating opportunities to buy other goods and services, boosting overall economic activity. The development and deployment of new energy technologies often require substantial investment in research, development, and infrastructure.

The adoption of certain energy technologies can influence energy price dynamics. For instance, an over-reliance on intermittent renewable sources may lead to price volatility, affecting businesses and consumers. Government policies and incentives related to energy technologies can impact revenue and expenditure. For example, subsidies for renewable energy or carbon pricing mechanisms can have fiscal implications.

In Table 1 some considerations about the macro-economic impact of solar, wind, hydro, and nuclear technology are presented.

Table 1 Considerations for macro-economic impact

	Technology	Considerations
1	Solar	Solar technology has a moderate potential for job creation, especially in installation and maintenance, the manufacturing being concentrated outside EU. Solar reduces dependence on imported fossil fuels, which can improve energy security and reduce trade deficits. The development of solar is dependent on incentives influencing the market.
2	Wind	Wind technology creates small number of local jobs, typically fewer jobs per megawatt compared to solar. Wind farms are often located in rural areas, injecting capital into these regions through land lease payments and tax revenues. Regions with strong wind resources can become net energy exporters, generating additional revenue.

3	Hydro	Hydroelectric power provides consistent baseload power, offering grid stability and reliability. Once constructed, hydroelectric plants can provide reliable power for many decades, contributing to long-term economic stability. Large hydro projects can have significant environmental and social impacts, leading to controversies and sometimes increased costs for mitigation.
4	Nuclear	Nuclear power plants require substantial upfront capital investment but offer long-term power generation with low fuel costs. Nuclear power plants create a lot of jobs during construction, operation, and decommissioning phases. Managing nuclear waste presents long-term costs and challenges.

References

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(Americo, 2023) Americo A et al, The energy transition and its macroeconomic effects, Monetary and Economic Department May 2023

IEA (2021) IEA, Renewables 2021.

Fiche 2.8, Applicability for cogeneration

Fiche – summary of data and considerations

Category of LCA assessment	Economics
Indicator	Applicability for cogeneration
Sub-indicator	-
Date of release	2023 July 17
Responsible partner	RATEN ICN
Contributing organizations	-
Authors	I. Prodea
Version	1.0

Cogeneration means that a plant supplies both electricity and heat, thus increasing the efficiency from 30-33% (usually, for heat conversion to the electricity) to 75-90%, [1], [2].

The mandatory condition to apply for cogeneration is that a technology to generate heat by burning a traditional fossil fuel or by fission reaction and also, nowadays, by concentrating the solar power (Concentrating Solar Power). As a result, only the Coal, Gas, Solar (CSP) and Nuclear technologies are suitable for cogeneration, the rest ones, Wind, Solar (PV) and Hydro not being able to apply for cogeneration (N/A).

Table 1 Applicability for Cogeneration

	Technology	**Applicability for cogeneration**
1	Coal	Applicable
2	Gas (NGCC plant)	Applicable
3	Hydro	N/A
4	Solar (CSP)	Applicable
5	Solar (PV)	N/A
6	Onshore W	N/A
7	Offshore W	N/A
8	Nuclear	Applicable

References

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https://www-pub.iaea.org/MTCD/Publications/PDF/P1862_web.pdf

[2] NON-ELECTRICITY PRODUCTS OF NUCLEAR ENERGY, NEA, 2004

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Fiche 2.9.1, Level of standards generated, rules and control - Maturity of the authorization process

Fiche – summary of data and considerations

Category of LCA assessment	Economics
Indicator	Maturity of the authorization process
Sub-indicator	-
Date of release	2023 July 17
Responsible partner	RATEN ICN
Contributing organizations	-
Authors	I. Prodea
Version	1.0

The authorization process for any type of plant producing energy is a laborious work, but there are differences between technologies and countries. In generally speaking, according to the references below, as older a technology is, a more mature its authorization process becomes. In Table 1 a scoring process was performed taking into account the age of a technology (10 points for the oldest) and the mean duration of the authorization process (10 points for the shortest period).

Table 1 Maturity of the authorization process

	Technology	**Age scoring**	**Duration of the authorization process scoring**	**Total score**
1	Coal	10	8	
2	Gas (NGCC plant)	8	8	
3	Hydro	9	6	
4	Solar (CSP)	3	9	
5	Solar (PV)	4	10	
6	Onshore W	4	8	
7	Offshore W	3	8	
8	Nuclear	8	7	

References

[1] N. Falcucci, A. Gerbeti, "Authorisation of plants and infrastructures"
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https://www.cga.ct.gov/2009/rpt/2009-R-0246.htm

[3] "Licensing Process for Nuclear Installations", IAEA SAFETY STANDARDS SERIES No. SSG-12, Vienna, 2010

[4] "New Report Examines the U.S. Hydropower Permitting Process", US Water Power Technologies Office, Oct., 2021, https://www.energy.gov/eere/water/articles/new-report-examines-us-hydropower-permitting-process

Fiche 2.9.2, Level of standards generated, rules and control - Level of industrial codes and standards

Fiche – summary of data and considerations

Category of LCA assessment	Economics
Indicator	Level of Industrial Codes and Standards
Sub-indicator	-
Date of release	2023 September 5
Responsible partner	RATEN ICN
Contributing organizations	-
Authors	I. Prodea
Version	1.0

According to [1, 2 and 3], there are several industry classification taxonomies used to segregate markets into sectors within the macroeconomy. For example, The ICB (Industry Classification Benchmark, [1]) uses a system of 11 industries, partitioned into 20 super-sectors, which are further divided into 45 sectors and 173 subsectors. The Global Industry Classification Standard (GICS, [2]) defines more super-sectors (24) and less sub-sectors (157). In both classifications the Energy sector is divided preponderantly in super-sectors allocated to the fossil fuel technology (oil, gas, coal), while the rest of energy technologies are allocated to the ”alternative energy” sector, see Table 1 and 2. As result, the older fossil fuel based technologies seem to have a higher level of standardization. Nevertheless, the nuclear technology benefits for a lot of specific international codes and standards, many of them being issued by the IAEA Vienna, [4] and Nuclear Energy Agency (NEA), [5].

Table 1. ICB Energy Classification, [1]

Energy	Oil Gas and Coal	Oil: Crude Producers (60101010)
		Offshore Drilling and Other Services (60101015)
		Oil Refining and Marketing (60101020)
		Oil Equipment and Services (60101030)
		Pipelines (60101035)
		Coal (60101040)
	Alternative Energy	Alternative Fuels (60102010)
		Renewable Energy Equipment (60102020)

Table 2. GICS Energy Classification, [2]

Energy	Energy Equipment & Services (101010)	Oil & Gas Drilling (10101010)
		Oil & Gas Equipment & Services (10101020))
	Oil, Gas & Consumable Fuels (101020)	Integrated Oil & Gas (10102010)
		Oil & Gas Exploration & Production (10102020)
		Oil & Gas Refining & Marketing (10102030)
		Oil & Gas Storage & Transportation (10102040)
		Coal & Consumable Fuels (10102050)

According to the bibliography, the level of standardization is considered to be "high" if a technology name explicitly appears in at least one classification and "moderate" if it doesn't, see Table 3.

Table 3 Level of Industrial Codes and Standards

	Technology	**Level of standardization**	**Total score**
1	Coal	High	
2	Gas (NGCC plant)	High	
3	Hydro	Moderate	
4	Solar (CSP)	Moderate	
5	Solar (PV)	Moderate	
6	Onshore W	Moderate	
7	Offshore W	Moderate	
8	Nuclear	Moderate	

References

[1] https://en.wikipedia.org/wiki/Industry_Classification_Benchmark

*[2] *** "Global Industry Classification Standard" by S&P Global Market Intelligence Company https://www.spglobal.com/marketintelligence/en/documents/112727-gics-mapbook_2018_v3_letter_digitalspreads.pdf*

[3] https://www.ftserussell.com

*[4] *** IAEA Safety Standards, https://www.iaea.org/resources/safety-standards*

*[5] *** Nuclear Energy Agency-Codes and Standards in Nuclear Safety*

https://www.oecd-nea.org/jcms/pl_24141/codes-and-standards-in-nuclear-safety

Fiche 2.9.3, Level of standards generated, rules and control - Needs for technical support

Fiche – summary of data and considerations

Category of LCA assessment	Economics
Indicator	Needs for Technical Support
Sub-indicator	-
Date of release	2023 September 12
Responsible partner	RATEN ICN
Contributing organizations	-
Authors	I. Prodea
Version	1.0

The following data are compiled from [1,2,3,4,5,6].

A strong technical support supposes to have a solid foundation of the basic concepts and tools that are relevant to a field of activity. Depending on the domain, this may include hardware, software, networking, security, cloud, databases, web development, and more. People involved in offering technical support must be familiarized with the common terms, acronyms, protocols, standards, and best practices that apply to their field of activity. There is no energy technology that doesn't need for technical support, this being required during the entire technology's lifetime, starting to the design stage, construction, commissioning, operation and decommissioning. The needs for technical support can be different, according to the stage and technology type. For example, the fossil fuel-based technologies need less highly qualified personnel and, accordingly, smaller needs for technical support than the nuclear technology, where about 1 of 2 employees have high skilled education.

The job creation, direct or indirect, by any technology is a positive aspect, but taking a look from the opposite side, it can be observed that at least the direct jobs created are required to run that technology. In this respect, the simply average ratio between the number of jobs needed to produce the unity of electric energy (1 GW), can be considered as a measure of the technical support needed to operate that technology, because the employees' skills serve to this goal. It is, let say, another kind of efficiency, the "job efficiency".

In Table 1 the average numbers of job accounted in power generating sector according to different technologies are calculated according to [2,3,4,5] and, in the last column, the needs for technical support are simply appreciated by three level: small needs, moderate needs and large needs.

Table 1 Needs for technical support

	Technology	**Installed capacity** (as by 2019, [6])	**Average number of jobs (mill.)**	**# of jobs/GWe**	**Needs for technical support**
1	Solar	740	3	4054	Large
2	Wind	625	1.2	1920	Moderate
3	Hydro	1200	1.9	1583	Moderate
4	Coal	1200	2	952	Small
5	Oil & gas	2220	1.4	630	Small

6	Nuclear	392	1	2551	Large*

*The technical support needs for Nuclear technology are also appreciated to be Large because this technology has the most high skilled jobs, compared to the rest of technologies

References

[1] https://www.linkedin.com/advice/3/how-can-you-develop-skills-competencies-succeed

*[2] *** "Renewable Energy and Jobs", Annual Review 2020, International Renewable Energy Agency (IRENA), https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2020/Sep/IRENA_RE_Jobs_2020.pdf?rev=db153791a7744a33913b553e02a1e5b0*

*[3] *** "Renewable Energy and Jobs", Annual Review 2020, International Renewable Energy Agency*

*[4] *** "Measuring Employment Generated by the Nuclear Power Sector", NEA OECD Publishing, Paris, 2018*

*[5] *** "World Energy Outlook 2021", International Energy Agency (IEA), www.iea.org/weo*

*[6] *** "World Energy Employment 2020", International Energy Agency (IEA),*

https://iea.blob.core.windows.net/assets/a0432c97-14af-4fc7-b3bf-c409fb7e4ab8/WorldEnergyEmployment.pdf

Fiche 3.1.1, Jobs created - Direct high-education jobs

Fiche – summary of data and considerations

Category of LCA assessment	Social
Indicator	Jobs created
Sub-indicator	Direct high-education jobs
Date of release	2023, July 19
Responsible partner	RATEN ICN
Contributing organizations	-
Authors	M. Apostol
Version	1.0

The following data are compiled from (Deloitte, 2019), (20th EurObserv'ER Report, 2020), (IRENA 2020), (IRENA 2020, Statistics), (WindEurope, Deloitte, 2017), (IRENA, Annual Review, 2021).

The direct high-education jobs created by nuclear power plants and wind are provided. The wind was chosen from different forms of renewable due data availability and the fact that it will be a major source of future renewable power. Direct employment refers to the employment at the power plant itself. Indirect employment encompasses jobs that supply products and services to plant activities.

In 2019, in the EU, nuclear installed capacity was 118 GW. The nuclear industry sustained 1,129,900 million jobs. 351,900 represented direct jobs (sustained directly through the industry's performance). These direct jobs indirectly sustained other 777,900 jobs. During the three nuclear lifetime phases (construction, operation and decommissioning), the share of direct jobs is as follows: 9,600 in construction, 258,600 in operation and 83,700 in decommissioning. Every direct job in the nuclear industry generates 2.2 indirect jobs throughout the EU labour force market. 47% of the labour force directly or indirectly employed by the nuclear sector in the EU is highly skilled. That means approximately 1 out of 2 employees in the nuclear industry in the European Union are highly skilled (Deloitte, 2019). Thus, we can consider that around 165,393 employees have a formal nuclear education background (bachelor – EQF6, master - EQF7, PhD – EQF8) and formal education in mechanical, electrical, civil engineering, systems (nuclearized Science, Technology, Engineering and Mathematics (STEM) professionals).

Around 1,235,000 persons were directly or indirectly employed in the European Union renewable energy sector (20th EurObserv'ER Report, 2020).

Wind energy was responsible in 2019 for 218,700 jobs in the EU, both directly and indirectly. Direct employment includes renewable equipment manufacturing, renewable plant construction, engineering and management, operation and maintenance, biomass supply and exploitation. Indirect employment refers to secondary activities, such as transport and other services (20th EurObserv'ER Report, 2020). The installed capacity from wind energy was 191.277GW (IRENA 2020, Statistics). To find the direct employment in 2019, the ratio between direct and indirect jobs in the wind energy industry for 2011, 2012, 2013, 2014, 2015 and 2016 was calculated (WindEurope,Deloitte, 2017). This is included into [1.17, 1.26] interval. An assumption was made that for 2019, the ratio is 1.3. Therefore, the direct jobs obtained are 123,613. Taking into consideration that in the electricity sector, the average share of highly skilled employees is considerably lower than in nuclear sector and currently varies between 25% and 36% (Deloitte, 2019), an interval for direct jobs of individuals with degrees in fields such science, technology, engineering and mathematics (STEM) has been obtained: [30,903, 44,500].

The sub-indicator "Direct high-education jobs" is presented in jobs/GWe.

Table 1 Direct high-education jobs

	Energy technology	Direct high-education jobs	Potential for improvement
1	Wind energy	[161, 233]	The 1.5°C Scenario (1.5-S) describes an energy transition pathway aligned with the 1.5°C climate ambition – that is, to limit global average temperature increase by the end of the present century to 1.5°C, relative to preindustrial levels (IRENA 2021). Examining needed jobs by education level in the renewable energy sector as a whole, shows that under a Paris-compliant 1.5°C scenario half of the globally 122 million jobs created by 2050 will require only a primary or lower secondary education. An additional 37% of occupations will need secondary education**.** The remaining 13% of jobs will require a tertiary education at the bachelor's, master's or doctoral level.
2	Nuclear	1,402	High Scenario with 150 GW installed nuclear capacity by 2050: Out of a total of 1,321,600 jobs (8,811 jobs/GW) that are sustained every year throughout the period 2020 – 2050 by the nuclear sector; in the future, 45% of the nuclear labour force will be highly skilled in the EU. In comparison with the current situation, the share of highly skilled professionals decreased by 2%, mainly due to the expected increase of employment during construction phase, which requires less qualified labour force compared to operation phase. (Deloitte, 2019).

References

(Deloitte, 2019) Deloitte, Economic and Social Impact Report, FORATOM, 25 April 2019

(20th EurObserv'ER Report, 2020) The State of Renewable Energies in Europe, Edition 2021

(IRENA 2020) International Renewable Energy Agency, Renewable Energy and Jobs, Annual Review 2020

(IRENA 2020, Statistics) International Renewable Energy Agency, Renewable Energy Statistics 2020

(WindEurope, Deloitte, 2017) Deloitte, Wind Europe, Local impact, global leadership. The impact of wind energy jobs and the EU economy, November 2017

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Fiche 3.1.2, Jobs created - Jobs in contributing industries

Fiche – summary of data and considerations

Category of LCA assessment	Social
Indicator	Jobs created
Sub-indicator	Jobs in contributing industries
Date of release	2023, July 13
Responsible partner	RATEN ICN
Contributing organizations	-
Authors	M. Apostol
Version	1.0

The following data are compiled from (Deloitte, 2019), (IRENA 2020), (IRENA 2020, Global Renewable Outlook) and (IRENA 2020, Statistics).

In 2019, there were 126 nuclear power reactors in operation in 14 European Union (EU) Member States, with a total estimated capacity of 118 GW.

The nuclear industry and its supply chain represent a significant employer, generating in 2019 1,129,900 direct and indirect jobs in the EU. 351,900 jobs were created within industry (direct jobs) which indirectly sustain other 777,900 jobs. These are jobs created through suppliers employees' and suppliers' employees expenses.

At the EU level, in 2019 total renewable electricity capacity was 497.267 GW (IRENA 2020, Statistics), as follows:

- 156.412 GW from hydropower;
- 191.277 GW from wind energy:
  - 169.448 GW from onshore wind energy;
  - 21.831 GW from offshore wind energy;
- 132.5 GW from solar energy:
  - 130.165 GW from solar photovoltaics (PV);
  - 2.335 GW from Concentrated solar power (CSP);
- 17.078 GW from other renewable energy (liquid biofuels, biogas, geothermal energy).

Estimated direct and indirect jobs in renewable energy in European Union, in 2019 was 1,317,000 jobs (IRENA 2020), that means a number of 2,648 jobs/GW sustained by renewable technology. Estimated jobs by each individual renewable energy technology are as follows:

- Hydropower: 78,000 jobs;
- Solar photovoltaics (PV): 127,000 jobs;
- Wind energy: 292,000 jobs;
- Liquid biofuels, biogas, geothermal energy: 354,000 jobs.

The sub-indicator *Jobs in contributing industries* is presented in jobs /GW of installed capacity with data available for 2019.

Table 1 Jobs in contributing industries

<table>
<tr><th></th><th>Energy technology</th><th>Jobs sustained by technology [jobs/GW]</th><th>Potential for improvement</th></tr>
<tr><td>1</td><td>Hydropower</td><td>499</td><td rowspan="5">Under the Transforming Energy Scenario (TES*), an estimation of 2,7 million jobs in 2050 in renewable energy at EU level is made.
In terms of technology, solar will account for 30% in Europe. Wind is strongest in the European Union, with about 25% of jobs. Energy transformation roadmap to 2050, foresees for TES a renewable installed capacity (bioenergy, hydropower, solar PV and wind) of 1,655 GW (IRENA 2020, Global Renewable Outlook).

High Scenario with 150 GW installed nuclear capacity by 2050:
Out of a total of 1,321,600 jobs (8,811 jobs/GW) that are sustained every year throughout the period 2020 – 2050 by the nuclear sector (Deloitte, 2019).</td></tr>
<tr><td>2</td><td>Wind energy</td><td>1,527</td></tr>
<tr><td>3</td><td>Solar photovoltaics (PV)</td><td>976</td></tr>
<tr><td>4</td><td>Other renewable energy (Liquid biofuels, biogas, geothermal energy)</td><td>20,764</td></tr>
<tr><td>5</td><td>Nuclear</td><td>9,575</td></tr>
</table>

*The "Transforming Energy Scenario (TES)" describes an ambitious, yet realistic, energy transformation pathway based largely on renewable energy sources and steadily improved energy efficiency (though not limited exclusively to these technologies). This would set the energy system on the path needed to keep the rise in global temperatures to well below 2 degrees Celsius (°C) and towards 1.5°C during this century.

References

(Deloitte, 2019) Deloitte, Economic and Social Impact Report, FORATOM, 25 April 2019

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Fiche 3.2, Impact on the local/regional business (partner with other business)

Fiche – summary of data and considerations

Category of LCA assessment	Social
Indicator	Impact on the local/regional business
Sub-indicator	-
Date of release	2023 July 30
Responsible partner	RATEN ICN
Contributing organizations	-
Authors	M. Constantin
Version	1.0

The following data are compiled from (IRENA_1, 2021), (IRENA_2, 2021), (NEA, 2018).

The deployment of energy sources has several impacts on the local and regional economy. These impacts can be both positive and negative, depending on various factors such as the type of energy, the scale of deployment, the local market conditions, and the level of government support. The positive impacts are related to: (1) Job Creation, (2) Investment and Business Opportunities, (3) Energy Independence, (4) Increased Tax Revenues, (5) Environmental and Health Benefits. The categories of negative impacts are: (1) Disruption of Existing Industries, (2) Land Use and Environmental Concerns, (3) Grid Integration Challenges, (4) Initial Investment Costs.

In terms of job creation, the current indicator considers only the jobs for the operation phase. In case of solar and wind the manufacturing is factory based, regularly abroad based. Limited impact on local business may be produced by all the technologies during the installing/construction phase, in terms of direct and indirect jobs, but the influence is strongly dependent on the site context.

Table 1 Job creation – operational phase jobs for some energy generation technologies

		Number of jobs per GWe (operation)	
		Min	**Max**
1	Solar*	20	40
2	Wind*	5	10
3	Hydro (small)*	1	5
4	Hydro (large)*	5	25
3	Nuclear *(NEA, 2018)*	500	1500

*Data calculated based on *(IRENA_1, 2021), (IRENA_2, 2021)*

In term of local/regional business the impact is created by: (1) services needed for the functionality of the energy unit, included the contribution of the employee to the increase of the local services market, (2) presuming, (3) taxes on the turnover. In the first case the changes in the flux of raw materials and consumables is a measure of the impact. Whereas a nuclear plant is changing a lot the local flux of raw materials and consumables, the others has almost no contribution to the local business. For the second case the prosumer effect is high for solar, reduced for wind and hydro (small) and zero for hydro (large) and nuclear. From the point of view of the turnover, generally there are no important differences assuming a unit of 1 GWe production for all technologies and the same value of the outcome.

Table 2 Impact on local/regional business of 1 GWe unit energy

		Considered level of impact		
		Influence on the size of market services	**Prosuming**	**Taxes**
1	Solar	Low	High	Medium
2	Wind	Low	Low	Medium
3	Hydro (small)	No impact	Low	Medium
4	Hydro (large)	Medium	No impact	Medium
3	Nuclear	High	No impact	Medium

Other possible impacts on the local/regional business: (1) attractivity of tourism, with a plus for large hydro, (2) impact on local education, with a potential plus for nuclear, (3) impact on the notoriety, with a plus for large hydro and nuclear, but also possible for solar and wind in case of large capacities.

References

(IRENA_1, 2021) IRENA, Renewable Capacity Statistics 2021

(IRENA_2, 2021) IRENA, Renewable Energy and Jobs, Annual Review 2021

(NEA, 2018) NEA, Measuring Employment Generated by the Nuclear Power Sector, OECD Publishing, Paris, 2018

Fiche 3.3, Additional goods and services created

Fiche – summary of data and considerations

Category of LCA assessment	Social
Indicator	Additional goods and services created
Sub-indicator	-
Date of release	2023 August 07
Responsible partner	RATEN ICN
Contributing organizations	-
Authors	M. Constantin
Version	1.0

The following elements and considerations are compiled from (IAEA_1, 2017), (IAEA_2, 2017), (IRENA, 2019), (EERE, 2023).

This indicator considers all the other services or products than electricity. The desalination or hydrogen production is considered another service/product if the energy unit is used directly for this activity, and not included in case of some excess of electricity is used for this purpose. This consideration is based on the difficulties produced by the intermittency of solar and wind. Even the hydrogen obtained by renewables is generally considered as green hydrogen, due to the fluctuation the overall efficiency of yje process is significantly reduced and more emissions are produced.

		Additional created services/products
1	Solar	Water pumps for agricultural irrigation, Illumination without the need for a traditional power grid connection, Solar desalinization of sea water, Hydrogen production, Solar charging stations for electronic devices, including integration into electric vehicles systems, Solar thermal systems can heat water for residential, commercial, and industrial use Solar drives the storage technologies (especially the battery)
2	Wind	Water pumps for agricultural irrigation, livestock watering, and remote water supply in areas without access to grid electricity. Hydrogen production, Desalination of sea water, Ships equipped with sails or wind-assisted propulsion systems Wind energy sector drives research in areas such as aerodynamics, materials science, and energy storage

3	Hydro	Water Management (such as flood control, water storage for irrigation and drinking water), Energy storage systems (pumped-storage hydropower plants), Hydroelectric reservoirs can become tourist attractions, including boating and fishing, Some hydropower systems are integrated with desalination processes, Small-scale hydro systems designed for rural and remote areas providing energy for local communities.
4	Nuclear	Cogeneration by waste heat utilization: district heating, industrial processes, or desalination, Production of radioisotopes for nuclear medicine (like imaging and cancer treatment), and other use (irradiation in industry, food, agriculture, smoke detectors, determination the age of rocks/minerals/artifacts), Space exploration, nuclear power sources used in space missions, providing reliable energy for spacecraft on long missions where solar power is not practical, Sterilization and preserving the food, extending its shelf life by destroying bacteria, parasites, and insects Nuclear industry drives research in fields such as materials science, nuclear medicine, and industrial radiography Some countries operate nuclear-powered naval vessels, which require specialized technology, training, and maintenance.

References

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(IRENA, 2019) IRENA, Hydrogen A Renewable Energy Perspective, 2019
(EERE, 2023) https://www.energy.gov/eere/office-energy-efficiency-renewable-energy

Fiche 3.4, Value of the knowledge generated and maintained for the future

Fiche – summary of data and considerations

Category of LCA assessment	Social
Indicator	Value of the knowledge generated and maintained for the future
Sub-indicator	-
Date of release	2023 August 07
Responsible partner	RATEN ICN
Contributing organizations	-
Authors	M. Constantin
Version	1.0

The following elements and considerations are compiled from (IAEA, 2020), (IAEA, 2017), (Grape, 2014).

The knowledge generated and maintained by various energy technologies, including solar, wind, hydro, and nuclear power, holds immense value for the future. Each technology contributes unique insights that can drive advancements in science, engineering, sustainability, and other fields. Insights gained from energy technologies expand our understanding of materials, mechanics, physics, and other scientific disciplines. Engineering solutions developed for energy systems can influence broader engineering projects and infrastructure development. Knowledge informs energy policy decisions, grid management strategies, and economic analyses related to energy generation and consumption

Table 1 Value of knowledge generated by these energy technologies

1	Solar	Solar energy research advances our understanding of photovoltaic (PV) technology, solar thermal systems, and energy storage solutions. Developments in solar cell materials, coatings, and technologies influence other applications, such as electronic devices and lightweight, flexible electronics Insights gained from solar energy systems drive innovations in energy-efficient building design, urban planning, and grid integration
2	Wind	Wind energy technology relies on sophisticated aerodynamic principles for turbine design Wind energy's intermittency encourages research into smart grid technologies and energy storage solutions, which have broader applications for energy management and stability The practice of monitoring remote wind turbines has led to advancements in remote sensing technologies and data communication systems
3	Hydro	in-depth knowledge of water management, river ecosystems, and environmental impacts Hydroelectric turbines and generators are marvels of mechanical engineering. Advances in this field benefit industries involving rotational machinery and energy conversion Knowledge of river ecology, fish migration, and sediment transport from hydroelectric projects informs conservation efforts in aquatic ecosystems

4	Nuclear	Nuclear power relies on deep insights into nuclear physics, materials, and radiation. These areas have applications in scientific research, medical diagnostics and treatment, materials development. Nuclear theory contributes to the deep understanding of matter and of energy Nuclear power's stringent safety protocols and risk assessments contribute to broader safety standards in high-risk industries and emergency response planning The challenges of nuclear waste management drive advancements in waste containment, disposal technologies, and long-term environmental protection

References

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Fiche 3.5, Impact on education

Fiche – summary of data and considerations

Category of LCA assessment	Social
Indicator	Impact on education
Sub-indicator	-
Date of release	2023, August 17
Responsible partner	RATEN ICN
Contributing organizations	-
Authors	M. Apostol
Version	1.0

The following data are compiled from (ENEN2plus D1.2 deliverable, 2023), (ENEN2plus D1.3 deliverable, 2023), (IAEA), (WNA), (MIT OpenCourseWare), (NEI), (ENEN), (Pact for Skills), (IRENA), (REW), (SEforALL).

The impact of both nuclear and renewable technologies on education are presented.

The nuclear technology has several impacts on education. In the following, some of the key aspects in which nuclear technology influences education are shortly discussed.

Unique skills: Education in the field of nuclear science and engineering equips individuals with a range of unique skills needed for working in nuclear domain. Some of the skills developed through education in this field are: nuclear waste management, decommissioning and dismantling (including R&D and planning), radiochemistry, water chemistry (including corrosion), radiation protection, nuclear instrumentation and control, quality management and inspection, reactor and hot lab operation, organizational and human factors, materials science and engineering (nuclear facility materials, failures, component engineering, inspections and lifetime management), nuclear and particle physics, reactor physics and dynamics, thermal hydraulics and coolants, risk analysis (including probabilistic risk assessments), safeguards, safety and security (business security and fire safety), severe accidents, etc. (ENEN2plus D1.2 deliverable, 2023).

Nuclear engineering programs: Many universities have created and offer attractive educational programs in nuclear engineering, preparing students (future professionals) for working in nuclear energy production, waste management and decommissioning, R&D institutes, Technical safety organization, Regulatory authorities, etc.

Research and training: Nuclear technology has advanced research capabilities in its related fields. Universities and research organizations often collaborate in the efforts to provides hand-on training and research opportunities for students. Many research facilities are open for students, in this way their practical skills and theoretical understanding contribute to a more comprehensive education.

Public awareness: Informing the general public about nuclear energy, its benefits, the associated risks and its responsible use, helps in creation of an educated and informed public that can participate in important societal discussions, including the decision-making process.

Educational networks: There are several available resources when it comes to educational networks and platforms focusing on nuclear energy. These platforms provide materials, courses and information on the nuclear technology. Below, some notable examples are provided:

International Atomic Energy Agency - IAEA: The IAEA is an international organization that promotes the peaceful use of nuclear energy. It offers various educational resources, including online and face-to-face courses and workshops, webinars, fellowship programs and schools on nuclear related topics, publications, and technical documents (IAEA);

World Nuclear Association - WNA: The WNA is a global industry organization that promotes nuclear power. Its website offers educational resources, including publications, reports, and fact sheets on various aspects of nuclear energy. The WNA's Knowledge Library provides in-depth information on nuclear power plants, fuel cycle processes, nuclear safety, economic aspects, etc. (WNA);

Massachusetts Institute of Technology - MIT OpenCourseWare: MIT offers free online access to course materials from various disciplines, including nuclear science and engineering (MIT OpenCourseWare);

Nuclear Energy Institute - NEI: The NEI is a trade association representing the U.S. nuclear energy industry. Their website features educational resources and information on nuclear technology, safety, and policy. They provide reports, fact sheets, and other materials to enhance public understanding of nuclear energy (NEI);

European Nuclear Education Network – ENEN: ENEN is an international nonprofit organization established under the Belgian law. The main purpose of the ENEN Association is the preservation and the further development of expertise in the nuclear fields by higher education and training in Europe (ENEN).

Non-power applications using ionizing radiation: The knowledge acquired in the using of nuclear technology (radiation protection and production/handling of radioactive materials) made possible the use of radioisotopes for medical applications which include both therapy (e.g., internal or external radiation therapy) and diagnosis (e.g., imaging). Other non-power applications include environment and space applications (ENEN2plus D1.3 deliverable, 2023).

The impact of renewable technologies (such as solar power, wind energy, hydropower, and others) on education is significant and can offer opportunities for hands-on learning, interdisciplinary studies, and sustainable practices. Bellow, some key aspects in which renewable technologies impact education are presented.

Skills: Education plays an important role in developing skills needed for the renewable energy sector. The following skills are typically fostered through education for the renewable energy industry: administrative, legal and technical/digital skills for staff in permitting authorities to process project permits and evaluate environmental impact assessments; engineering, digital, automation and scientific skills; design, installation, operation and maintenance of renewable energy technologies; planning and project management; occupational health and safety; energy system integration; data analysis and modeling; communication and collaboration; entrepreneurship and business acumen, etc. (Pact for Skills).

Stimulating interest in STEM field: The integration of renewable technology in education can stimulate the interest of students in STEM (Science, Technology, Engineering, and Mathematics) field. They can see the transformation of scientific concepts in practical applications and become inspired to pursue careers in renewable energy, sustainability and environmental conservation, etc.

Hands-on learning opportunities: Integrating renewable technologies into educational programs allows students to be engaged in practical, hands-on experiences. Schools and universities can install solar panels, wind turbines, or other renewable energy systems on their campuses, in this way offering students the possibility to analyze these systems. This promotes practical learning and helps students to develop valuable technical, critical thinking and problem-solving skills.

Interdisciplinary studies: Renewable technology offers a platform for interdisciplinary studies, encompassing aspects of science, technology, engineering, mathematics, environmental studies, economics, social science and humanities, and more. This encourages collaboration among students from various disciplines, helping them in understanding the global perspective on energy challenges and solutions.

Research opportunities: Renewable technology introduces opportunities for research and innovation within educational institutions. Students and faculties can collaborate on projects on the improving the efficiency and effectiveness of renewable energy systems.

Educational networks: There are many educational networks and platforms focusing on renewable energy and sustainability. They offer courses, resources, and information to help individuals to learn about renewable energy technologies, climate change mitigation, and sustainable practices. Below, some notable examples are provided:

International Renewable Energy Agency - IRENA: IRENA is an intergovernmental organization dedicated to promote the adoption and use of renewable energy worldwide. It provides educational resources, publications, and reports on renewable energy technologies, policy frameworks, and market analysis (IRENA);

Renewable Energy World – REW: REW is an online platform that offers news, analysis, and insights related to renewable energy. They publish articles, interviews, and technical resources that can help individuals stay up-to-date with the latest advancements in the field (REW);

Sustainable Energy for All - SEforALL: SEforALL is an international organization aiming to accelerate sustainable energy solutions. It offers various resources and publications on sustainable energy, including reports, case studies, and toolkits. These resources can help individuals deepen their understanding of renewable energy and related topics.

References

(ENEN2plus D1.2 deliverable, 2023) ENEN2plus - Deliverable D1.2 Report on Human Resources needs in Research, Safety and Waste Management, Project Number: 101061677, 31.05.2023, https://www.enen2plus.eu/fileadmin/user_upload/ENEN2plus_D1_2_20230531.pdf

(ENEN2plus D1.3 deliverable, 2023) ENEN2plus - Deliverable D1.3 Report on HR needs in non-power nuclear sector applications, Project Number: 101061677, 31.05.2023, https://www.enen2plus.eu/fileadmin/user_upload/ENEN2plus_D1_3_20230531.pdf

(IAEA) International Atomic Energy Agency, https://www.iaea.org

(WNA) World Nuclear Association, https://www.world-nuclear.org/

(MIT OpenCourseWare) Massachusetts Institute of Technology OpenCourseWare, https://ocw.mit.edu/

(NEI) Nuclear Energy Institute, https://www.nei.org/

(ENEN) European Nuclear Education Network, https://enen.eu

(Pact for Skills) European Commission, Pact for skills for the renewable energy sector, https://pact-for-skills.ec.europa.eu/system/files/2023-04/20230321%20-%20RE%20Skills%20partnership-%20Declaration%20%282%29.pdf

(IRENA) International Renewable Energy Agency, https://www.irena.org

(REW) Renewable Energy World, https://www.renewableenergyworld.com/

(SEforALL) Sustainable Energy for All, https://www.seforall.org/

Fiche 3.6, Contribute to the reduction of inherited burdens (toxic wastes, military stocks)

Fiche – summary of data and considerations

Category of LCA assessment	Social
Indicator	Contribute to the reducing of inherited burdens (toxic wastes, military stocks)
Sub-indicator	-
Date of release	2023 August 06
Responsible partner	RATEN ICN
Contributing organizations	-
Authors	M. Constantin
Version	1.0

The following elements and considerations are compiled from (IAEA, 2020), (IAEA, 2017), (Grape, 2014).

Toxic waste refers to hazardous materials that can cause serious harm to human health and the environment if not managed and disposed of properly. Various sources are present, including industrial processes, agriculture, healthcare, and household products. Many countries faced challenges related to the cleanup and proper management of toxic waste sites, such as abandoned industrial facilities and landfills containing hazardous materials. These sites can leach pollutants into soil and water, posing significant health risks to nearby communities and ecosystems.

Military stocks refer to excess or obsolete weapons, ammunition, and other military equipment that were accumulated during periods of conflict or heightened military buildup. These surplus military stocks can present challenges when it comes to storage, disposal, and preventing their illicit spread. Such stocks might include unexploded ordnance, aging chemical weapons, and radioactive materials. International treaties and agreements have been established to manage and eliminate certain categories of military stocks. For instance, the Chemical Weapons Convention aims to eliminate chemical weapons and their production facilities, while various arms control agreements aim to reduce the stockpiling of conventional weapons.

Nuclear power generates electricity through nuclear reactions, primarily involving uranium or plutonium isotopes. Therefore, nuclear power has a high potential to use the existing military stocks by transferring nuclear materials from military programs to peaceful purposes, such as using weapons-grade uranium for nuclear power generation.

GenIV technologies, based on fast spectrum reactors, may easily burn not only the stocks of uranium and plutonium, but also can transmute the dangerous inventory of the existing nuclear wastes.

On the other hand, nuclear power technologies, particularly those related to handling and managing radioactive materials, can be leveraged to ensure the safe decommissioning of military stocks. Expertise gained from civilian nuclear power programs can contribute to the safe handling of radioactive materials from military applications.

Renewable energy technologies can play an indirect role in the effort to reduce the current inherited burdens (toxic wastes, military stocks) at the world level. The repurposing of military sites or resources is possible, for example the decommissioned military facilities and installations can be transformed into sites for renewable energy projects, such as solar farms or wind turbines. These initiatives not only provide clean energy but also utilize existing infrastructure, reducing the burden of maintaining unused military sites.

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(IAEA, 1997) IAEA, Nuclear Fuel Cycle and Reactor Strategies: Adjusting to New Realities, 1997

(Grape, 2014) S. Grape et al, New perspectives on nuclear power—Generation IV nuclear energy systems to strengthen nuclear non-proliferation and support nuclear disarmament, Energy Policy, v. 73, 2014, p. 815-819

Fiche 3.7, Impact on health improvement

Fiche – summary of data and considerations

Category of LCA assessment	Social
Indicator	3.7 Impact on health improvement
Sub-indicator	-
Date of release	2023 September 15
Responsible partner	RATEN ICN
Contributing organizations	-
Authors	M. Constantin
Version	1.0

The following elements and considerations are compiled from (Seddighi, 2023), (SWP, 2019).

The impact of the energy technologies on health improvement can be assessed comparatively, taking into account various factors such as air and water pollution, safety risks, and long-term health benefits. Solar and wind technologies have a generally positive impact on health due to their minimal emissions and low safety risks. Hydroelectric energy can also contribute positively to health if its environmental impacts are carefully managed. Nuclear energy, while low in emissions, carries potential health risks associated with accidents. On the other hand, the development of nuclear sector contributed a lot to the development of nuclear medicine (radiopharmaceuticals, imaging procedures, diagnostic applications, therapeutic applications, etc.) with high benefits on the health improvement.

A comparative overview of the considered technologies is presented in Table 1.

Table 1 Impacts of some energy technologies on health improvement

	Technology	Considerations
1	Solar	Solar panels generate electricity without emitting greenhouse gases or air pollutants, contributing to cleaner air and reducing the risk of respiratory diseases and cardiovascular diseases.
2	Wind	Wind turbines produce electricity without emitting air pollutants, promoting cleaner air and reducing the risk of respiratory illnesses. Wind energy systems have a relatively low risk of accidents or health hazards when compared to some other forms of energy generation.
3	Hydro	Hydroelectric power plants produce electricity without direct emissions of air pollutants, resulting in improved air quality and reduced health risks. The construction of large dams can have ecological and health impacts by altering local water ecosystems, potentially affecting water quality and aquatic life.
4	Nuclear	Nuclear power plants generate electricity with minimal greenhouse gas emissions, contributing to climate change mitigation. If operated safely, nuclear energy can provide a stable source of low-carbon electricity, which can indirectly contribute to improved air quality and reduced climate-related health

		risks. Nuclear accidents, though rare, can have severe health consequences, including radiation exposure, which can lead to cancer and other health issues.

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(SWP, 2019) Keim M. et al, The Link Between Healthcare and Energy Supply, Stiftung Wissenschaft und Politik, 2019

Fiche 3.8, Impact on poverty

Fiche – summary of data and considerations

Category of LCA assessment	Social
Indicator	3.8 Impact on poverty
Sub-indicator	-
Date of release	2023 September 15
Responsible partner	RATEN ICN
Contributing organizations	-
Authors	M. Constantin
Version	1.0

The following elements and considerations are compiled from (Zhao, 2022), (Raspaud, 2012), (Sadiq, 2023).

The impact of these energy technologies on poverty is complex depending on several factors such as geographical location, scale of implementation, policy support, economic considerations, etc. While renewable energy sources like solar and wind often have more direct and widespread positive impacts on poverty through job creation and reduced energy costs, hydro and nuclear energy can have mixed effects that depend on careful management and community engagement. However, the nuclear and hydro may create a most affordable electricity with direct impact on the poverty, and on the economic development. A comparative overview of the considered technologies is presented in Table 1.

Table 1 Level of social adoption for some energy technologies

	Technology	Impact on poverty	Considerations
1	Solar	Positive Impact on Poverty Alleviation	Solar energy can have a positive impact on poverty alleviation, especially in regions with abundant sunlight. Solar panels can provide clean and affordable electricity to remote or underserved communities that may not have access to the grid. Solar power can lower energy bills for households, and may produce income in the prosumer option. The solar industry can create jobs in installation and maintenance (and very limited in the production), which positive impact on local economies reducing unemployment and poverty.
2	Wind	Positive Impact on Poverty Alleviation	Wind energy can create a limited number of jobs (mainly for maintenance, very limited for manufacturing and installation,) in the areas with wind resources. Wind farms often provide financial benefits to local communities through land lease agreements and tax

			revenues, which can be reinvested in social programs to combat poverty. Wind power can lead to lower energy costs for consumers.
3	Hydro	Mixed impact	In some regions, hydroelectric dams have played a significant role in providing electricity and water resources for communities, contributing to poverty reduction. The construction and operation of hydroelectric facilities can lead to the development of infrastructure, including roads and schools, which can improve living conditions in the surrounding areas. It's important to note that large-scale hydroelectric projects can also have negative social and environmental impacts, such as displacement of communities and disruption of ecosystems.
4	Nuclear	Mixed Impact	Nuclear energy provides a stable and low-carbon source of electricity contributing to a most affordable electricity and stimulating development. However, the high capital costs and long construction times can make nuclear investments less feasible in some regions. Nuclear power plants require highly skilled workers, which can create high-paying jobs in the communities where they are located. Safety concerns and the potential for accidents can have a negative impact on public perception, which can affect poverty indirectly through economic stability.

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Fiche 3.9, Social level adoption of the technology

Fiche – summary of data and considerations

Category of LCA assessment	Social
Indicator	3.9 Social level adoption of the technology
Sub-indicator	-
Date of release	2023 September 15
Responsible partner	RATEN ICN
Contributing organizations	-
Authors	M. Constantin
Version	1.0

The following elements and considerations are compiled from (IAEA, 2016), (Piven, 2022), (Brambati, 2022).

The level of social adoption for different energy technologies can vary significantly depending on a multitude of factors such as public perception, policy support, economic considerations, and environmental concerns. A comparative overview of the social adoption of the considered technologies is presented in Table 1.

Table 1 Level of social adoption for some energy technologies

	Technology	Level of social adoption	Considerations
1	Solar	High Social Adoption	Solar energy has gained significant social acceptance and adoption in many regions due to its decentralized nature, environmental benefits, and perceived simplicity. Solar panels are highly visible, and homeowners have the option to install them on their properties. The prosumer option enhances the social acceptance.
2	Wind	Moderate to High Social Adoption	Wind energy has been adopted widely in some regions, particularly those with favorable wind conditions. However, it may face more resistance in areas where people have concerns about the visual impact and noise associated with wind turbines. Public perception of wind energy can be influenced by environmental factors, such as concerns about bird and bat collisions, and the impact on local landscapes.
3	Hydro	High Social Adoption in Established Areas	Hydroelectric power has a long history and is widely accepted in regions where hydroelectric dams have been in operation for decades.

			New hydroelectric projects may face opposition due to concerns about their impact on river ecosystems, aquatic life, and displacement of communities.
4	Nuclear	Varies Widely	Social acceptance of nuclear energy varies significantly by country and region. Some countries have embraced nuclear power as a reliable and low-carbon energy source, while others have significant opposition due to concerns about safety, nuclear waste disposal, and the potential for accidents. Public perception of nuclear energy is often influenced by high-profile accidents like Chernobyl and Fukushima, which have led to increased skepticism in some regions. Nuclear energy's social adoption can also be influenced by government policies and incentives.

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Fiche 3.10, Existing investment in RDI to develop the technology

Fiche – summary of data and considerations

Category of LCA assessment	Social
Indicator	3.10 Existing investment in RDI to develop the technology
Sub-indicator	-
Date of release	2023 September 19
Responsible partner	RATEN ICN
Contributing organizations	-
Authors	M. Constantin
Version	1.0

The following elements and considerations are compiled from (IEA, 2021), (Jiang, 2023), (Howarth, 2019).

Investments in Research, Development, and Innovation (RDI) for different energy technologies are dependent on the technology maturity, regulatory environments, targeted performances. Due to the climate crisis and need to reach the market performances, solar and wind technologies have received significant RDI investments in the last decades. Hydroelectric power, being a mature technology, sees fewer investments but continues to benefit from incremental improvements especially for new developments of small hydro. Nuclear technology is a mature technology, but still receive large amount of investment to develop new systems like advanced reactors, Generation IV systems or SMRs. At the same time, funds are allocated for safety to make it a more viable option for low-carbon energy. The allocation of resources among these technologies depends on government policies, market dynamics, and societal priorities.

In Table 1 some considerations about the investment in RDI for solar, wind, hydro, and nuclear are presented.

Table 1 Investment in RDI for some energy technologies

	Technology	**Considerations**
1	Solar	Substantial RDI investments in recent years were driven by the market needs - decreasing costs and increased efficiency of photovoltaic (PV) panels. Governments, private companies, and research institutions have allocated significant funds to improve solar cell technologies, energy storage solutions, , reducing manufacturing costs, developing next-generation materials, and integration into existing power grids.
2	Wind	Wind energy has received substantial RDI investments, particularly for wind turbine improvements. Advancements in blade design, materials, and offshore wind technology have been a major focus. Wind energy research also addresses grid integration, storage solutions, and improvements in turbine efficiency to harness low wind speeds effectively.
3	Hydro	Hydroelectric power is a mature technology with fewer ongoing RDI investments compared to solar and wind.

4		Investments in hydro often target dam and turbine maintenance, efficiency improvements, and environmental impact reduction. RDI effort was devoted to new dam designs, but the potential for large-scale expansion is limited by geographical and environmental constraints.
4	Nuclear	Nuclear technology has experienced fluctuating levels of RDI investments due to safety concerns, regulatory challenges, and public perception. Investments are focused on enhancing the safety and efficiency of existing nuclear reactors, exploring advanced reactor designs (e.g., Gen IV, small modular reactors), and reducing nuclear waste. Research is essential to address safety issues and gain public trust while pursuing nuclear as a low-carbon energy option.

References

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Fiche 3.11, Dependency on government support (funding/ incentives, such as tax credits or subsidies)

Fiche – summary of data and considerations

Category of LCA assessment	Environment
Indicator	Dependency on the government support (funding or incentives, such as tax credits or subsidies)
Sub-indicator	-
Date of release	2023 September 01
Responsible partner	RATEN ICN
Contributing organizations	-
Authors	M. Constantin
Version	1.0

The following data are compiled from (Sikandar, 2021), (Zeinab, 2015).

Nuclear energy often relies heavily on government support due to its high upfront capital costs, long planning and construction periods, and regulatory complexities. Governments typically provide financial incentives and support in various ways, including loan guarantees, research funding, and regulatory oversight. Public perception, safety concerns, and the management of radioactive waste are significant challenges for the nuclear industry, which may necessitate ongoing government support for research, development, and waste disposal solutions.

Solar energy has historically depended on government support, especially in its early stages, to incentivize adoption and reduce costs. Support includes investment tax credits, rebates, feed-in tariffs, and research grants. As solar technology has matured and costs have decreased, the dependency on government support has decreased in some regions. Solar energy is increasingly competitive with conventional fossil fuels in many markets.

Wind energy has relied on government support in the form of tax incentives, production tax credits, grants, and regulatory frameworks that encourage wind farm development. Similar to solar energy, the wind industry has seen a reduction in dependency on government support as wind turbine technology has advanced and economies of scale have been realized.

Hydroelectric power, especially large-scale projects, often requires substantial government support for initial investment, dam construction, and environmental compliance. Environmental concerns, such as habitat disruption and river ecosystem impacts, have led to increased regulatory scrutiny and mitigation efforts, which can increase the cost and complexity of hydroelectric projects.

Financial incentives for nuclear, solar, wind, and hydro energy projects can vary significantly by country and region. In Table 1 some general examples of financial incentives are presented.

Table 1 Government support

	Technology	Type of support	Description
1	Nuclear	Loan Guarantees	Government guarantees the loan for the investment
		Production Tax Credits	Government provides a tax credit for each MWh of electricity produced
2	Solar	Investment Tax Credits	Government provides a tax credit based on the project's capital investment
		Feed-in Tariffs (FiT)	FiT guarantees fixed payments for solar energy producers, often for a specified period
		Renewable Energy Certificates (REC)	owners can earn RECs for each megawatt-hour of electricity generated. These certificates can be sold to utilities or other entities to meet renewable energy mandates
3	Wind	Production Tax Credits (PTCs)	Government provides a tax credit for each MWh of electricity produced
		Investment Tax Credits (ITC)	Government provides a tax credit based on the project's capital investment
		Renewable Portfolio Standards (RPS)	RPS policy mandates a certain percentage of electricity come from renewable sources, including wind
4	Hydro	Grants and Funding	Governments provide grants and funding for the development of hydroelectric projects, especially for smaller-scale installations or projects that include environmental mitigation measures
		Power Purchase Agreements (PPAs)	Utilities or other entities may enter into long-term PPAs with hydroelectric power producers, ensuring a market for the electricity generated and providing a stable revenue stream.
		Tax Incentives	Similar to those offered to other renewable energy sources, such as investment tax credits or depreciation benefits

References

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Fiche 3.12.1, Risks - Level of risk reflected in insurance needs

Fiche – summary of data and considerations

Category of LCA assessment	Social
Indicator	Risks
Sub-indicator	Assurance needs
Date of release	2023 August 05
Responsible partner	RATEN ICN
Contributing organizations	-
Authors	M. Constantin
Version	1.0

The following elements and considerations are compiled from (LLOYDS, 2020), (NRC, 2023), (ALTRAN, 2011), (Insurance, 2023), (Market, 2023).

In Table 1 the main operational risks considered to be part of an insurance service are presented. This offers a general image on the potential risks of each technology, for the operational phase. The risks of the investment, respectively the preparation and implementation phases are not discussed here.

Table 1 Main operational risks considered for insurance

	Energy	Operational risks considered for insurance
1	Solar	Equipment Degradation and Failures (panels and associated equipment like inverters and trackers can degrade over time due to weather conditions, temperature fluctuations, and manufacturing defects)
		Weather-Related Risks (solar installations are exposed to weather elements such as hail, storms, and heavy snowfall. Severe weather events can damage solar panels, reducing their efficiency and causing downtime.)
		Cybersecurity and Data Risks (hacking attempts on control systems can disrupt operations and compromise sensitive information)
		Health and Safety Concerns (potential health and safety hazards for workers)
		Performance Variability (sunlight availability influences the performances, insurance coverage can help compensate for the resulting revenue shortfalls)
		Supply Chain Disruptions (may introduce delays in the maintenance)
		Grid Connection and Regulatory Risks (issues with grid connection or changes in regulatory policies can affect energy production and revenue generation, the insurance coverage can help mitigate financial losses)
		Natural Disasters (earthquakes, wildfires, or other natural hazards can cause substantial damage to equipment and infrastructure, the insurance should cover the financial impact of such disasters.)
2	Wind	Equipment Failure (like gearboxes, generators, and blades)

		Weather-Related Risks (damages and operational disruptions by high winds, lightning strikes, hail, and extreme temperatures)
		Human Error and Maintenance Issues (Improper maintenance practices or human errors during maintenance can result in accidents, injuries, and damage to equipment)
		Cybersecurity Vulnerabilities (wind farms become more digitally integrated, facing increased cybersecurity risks such as disrupt operations and compromise sensitive information.)
		Environmental and Regulatory Risks (environmental incidents, such as oil leaks from gearboxes, can have ecological consequences)
		Health and Safety Concerns (potentially hazardous work environments, especially during construction and maintenance)
		Supply Chain Disruptions (geopolitical issues, transportation problems, or material shortages can lead to delays in maintenance and repair activities)
3	Hydro	Equipment Failures (turbines, generators, transformers, control systems, etc)
		Natural Hazards (hydro facilities are susceptible to natural disasters like floods, landslides, earthquakes, and severe weather events with significant damage potential to infrastructure and equipment
		Water Supply Variability (droughts, changes in water flow patterns, and water quality issues can impact energy generation, insurance coverage can help compensate for revenue shortfalls)
		Sedimentation and Reservoir Management (proper reservoir management is crucial to prevent excessive sedimentation, insurance impacts can involve coverage for the costs of sediment removal and reservoir maintenance)
		Environmental and Regulatory Risks (liability insurance can help cover costs related to regulatory violations and legal disputes for example on the obtaining of different permits)
		Infrastructure Aging (hydro facilities, such as dams and penstocks, can deteriorate due to factors like corrosion and wear)
		Health and Safety Concerns (potential hazards for workers)
4	Nuclear	Radiation and Safety Hazards (accidents, leaks, or breaches in containment systems can lead to radiation exposure for workers, the public, and the environment. Insurance coverage is crucial to address medical expenses, compensation for injuries, and cleanup costs associated with radiation incidents)
		Equipment Failures (reactors, steam generators, cooling systems, control systems, etc)
		Natural Disasters (extreme events like earthquakes, tsunamis, and hurricanes can still pose risks; damage to critical infrastructure or safety systems can result in accidents and contamination)
		Waste Management (failure in waste management systems can lead to environmental contamination and regulatory violations)

		Terrorism and Security (sabotage or theft of radioactive materials can have catastrophic consequences)
		Community and Public Relations (accidents or safety concerns can lead to public panic, negative media coverage, and legal claims)
		Long-Term Decommissioning (it involves managing radioactive materials, dismantling structures, and environmental restoration; insurance coverage can be important to address the costs and liabilities associated with decommissioning)
		Human Error (human errors can lead to accidents or operational disruptions)
		Regulatory and Compliance Risks (non-compliance with regulations or failure to meet safety standards can result in fines, legal actions, and plant shutdowns; liability insurance can help cover costs related to regulatory violations and legal disputes)
		Supply Chain Disruptions (business interruption insurance can assist in covering financial losses resulting from supply chain disruptions)

The cost of the failure of an equipment may introduce more understanding. It is clear the failure of a turbine or other critical equipment, in hydro and nuclear plant, produce a major impact and insurance efforts. In case of wind "a total blade failure can lead to a claim ranging from $150,000 to $500,000, considering the cost of the crane, crew and materials" (Insurance, 2023). In case of hydro or nuclear the cost of a turbine is $15000-$20000 per MWe.

The highest level of insurance effort is in the nuclear sector. In the US, *c*urrently, "the owners of nuclear power plants pay an annual premium for $450 million in private insurance for offsite liability coverage for each reactor site (not per reactor)" (NRC, 2023).

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Fiche 3.12.2, Risks - Proliferation of sensitive materials

Fiche – summary of data and considerations

Category of LCA assessment	Social
Indicator	Risks
Sub-indicator	Proliferation of sensitive materials
Date of release	2023 August 05
Responsible partner	RATEN ICN
Contributing organizations	-
Authors	M. Constantin
Version	1.0

The following elements and considerations are compiled from (UNO, 2017), (IRENA, 2021), (ISF, 2007).

The proliferation of sensitive materials in the energy sector refers to the potential spread of materials that could be used for both peaceful and non-peaceful purposes within the field of energy production.

Mainly the issue was raised by the nuclear energy sector referring to the potential spread of materials that are crucial to produce nuclear power, including both peaceful uses and the potential for weapons development. The spread of nuclear enrichment technologies and fissile materials raises concerns about the potential for countries or non-state actors to acquire the capabilities to build nuclear weapons. The main challenges and concerns are: (1) nuclear weapons proliferation (same materials used in civilian nuclear reactors, such as enriched uranium or plutonium, can be diverted for the production of nuclear weapons), (2) dual-use of technologies (both peaceful and military purposes), (3) security risks (the proliferation of sensitive materials can lead to security risks, including theft, sabotage, and attacks on nuclear facilities), (4) geopolitical tensions (proliferation can exacerbate geopolitical tensions, especially in regions where there are existing conflicts or power struggles).

In order to prevent the spread of nuclear weapons and weapons technology an international treaty (Non-Proliferation Treaty, NPT) was created in 1968. Around 190 states signed the NPT.

Even the issue is specific for nuclear sector, the proliferation of the sensitive materials may be a issue in the development of renewable sector. Here some elements to be considered in the assessment of the indicator:

Solar energy: (i) use of rare materials like tellurium and indium, which can be scarce and have environmental impacts during extraction, and can create vulnerabilities and geopolitical tensions, (ii) improper recycling and disposal are essential due to the presence of hazardous materials.

Wind: (ii) wind turbines use rare earth metals, leading to supply chain vulnerabilities and geopolitical dependency, (ii) recycling of wind turbine components and rare earth metals can be challenging.

Hydro: water resources can lead to conflicts between energy, agriculture, and ecology, and may initiate geopolitical conflicts.

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Fiche 3.13.1, Equality of opportunities - Women's empowerment

Fiche – summary of data and considerations

Category of LCA assessment	Social
Indicator	Equality of opportunities
Sub-indicator	Women's empowerment
Date of release	2023 August 03
Responsible partner	RATEN ICN
Contributing organizations	-
Authors	M. Constantin
Version	1.0

The following data are compiled from (IRENA_1, 2021), (IRENA_2, 2021), (NEA, 2023), (SEIA, 2023).

The exact share of women in the different energy sector varies by region, job role, and level of seniority. Women have often been underrepresented in technical and engineering roles within the energy sector.

Efforts to increase gender diversity and inclusion in the energy industry have been ongoing, and there has been a growing recognition of the importance of having a diverse workforce. Many organizations and initiatives have been working to promote opportunities for women in all sectors of the energy industry.

Table 1 Women employment in diverse energy generation technologies

		Total share	Share in STEM positions
1	Renewable (global)	32% (IRENA_2, 2019)	28% (IRENA_1, 2021)
2	Wind	21% (IRENA_2, 2019) With the following distribution: • STEM 28% • Non-STEM professionals 35% • Administrative professionals 45%	14% (IRENA_1, 2021)
3	Solar	26% (data limited to US case) (SEIA, 2023)	
4	Oil and gas	22% (IRENA_2, 2019)	
5	Nuclear *(NEA, 2023)*	24.9% (NEA, 2023) • STEM 20.6% • senior leadership roles 18.3%	20.6% (NEA, 2023)

References

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Fiche 3.13.2, Equality of opportunities - For minorities, vulnerable social groups, Indigenous peoples, children, people with disabilities

Fiche – summary of data and considerations

Category of LCA assessment	Social
Indicator	Equality of opportunities
Sub-indicator	Minorities equality, children, indigenous peoples, people with disabilities
Date of release	2023 August 04
Responsible partner	RATEN ICN
Contributing organizations	-
Authors	M. Constantin
Version	1.0

The following elements and considerations are compiled from (DIVERSION, 2021), (UNICEF, 2022), (Hoicka, 2021), (IISD, 2023), (ILO, 2023).

The energy sector has faced challenges related to minority equality. Historically, certain minority groups have been underrepresented in the sector, particularly in leadership positions and technical roles. However, continuous efforts have been made by all the energy technologies to promote diversity and inclusion through initiatives such as targeted recruitment, mentoring programs, and diversity training.

In terms of the impact on minorities the most representative issue is the need of land of different energy technologies. The renewables, especially PV, require large surfaces of land. Large-scale hydro projects, such as dams, can significantly impact minority communities through displacement and disruption of traditional ways of life. The renewables development must engage with local communities, including minority groups, to address concerns and provide economic opportunities

In case of nuclear energy even the surface of land is more reduced, the exclusion zone around a nuclear plant, introduce more limitations in the local development. The risks associated with nuclear accidents or waste storage create a potential impact and discomfort. Transparency and meaningful engagement with local communities, including minorities, are essential in the nuclear sector due to safety and environmental concerns.

The impact on the children may be considered in terms of: (1) air quality improvement, and, (2) safety. The renewables and nuclear are energy with reduced or zero emissions, all of them improving the air quality. In case of safety, measures to eliminate safety hazard are necessary for all technologies (correct installing of solar panels, fencing of wind turbines, minimization of risk of flooding at hydro dams, stringent regulations and emergency preparedness to avoid long-term health impacts on children in case of a major incident).

The impact on the indigenous peoples can vary significantly based on the context of the site, project, and level of community engagement. Land use is the main issue in case of solar and wind, land and water use in case of hydro, and land and safety in case of nuclear. The specificities of the projects may lead to displacement or altered land use for all technologies, with a strong impact in case of hydro large dams. Hydro projects often intersect with indigenous rights to land and resources. In case of nuclear, indigenous communities may express concerns about nuclear safety and waste disposal due to potential long-term environmental impacts.

The impact on the people with disabilities may be discussed in terms of Physical Accessibility and Inclusive Design.

Solar installations typically have minimal physical barriers, making them relatively accessible for people with mobility impairments. Wind farms might involve uneven terrain, which could pose challenges for people with mobility impairments. Onshore wind installations might require careful planning to ensure accessibility. Large hydro projects might have areas with potential physical barriers, such as reservoirs or dam structures. Ensuring proper fencing, signage, and safety measures is essential for all visitors, including those with disabilities. Nuclear facilities often have strict security measures, which could create challenges for people with disabilities in terms of access and mobility within certain areas.

Solar and wind energy facilities can be designed with inclusive features such as accessible pathways and equipment. Consideration of pathways, signage, and controls can enhance inclusivity. The new hydroelectric facilities are designed to accommodate people with disabilities, the older designs are adapted. This includes accessible pathways, ramps, and controls to ensure that all visitors can safely enjoy the area. In case of nuclear facilities, accessible routes, controls, and information for people with disabilities were introduced in EU case, considering the balancing of safety concerns with inclusivity.

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