ECONOMIC AND SOCIAL CONSIDERATION FOR THE FUTURE OF NUCLEAR ENERGY

Stakeholder demands for participatory technology assessment of energy sources for the green transition

Recommendations to improve the ECOSENS methodology

Final deliverable of ECOSENS Task 2.3

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With thanks for their thoughtful feedback throughout the life cycle of WP2:

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ECOSENS is a 3-year project (2022-2025) funded by the Euratom Research and Training Programme. It aims to create a neutral space where specialists in social sciences (including economics, sociology, social psychology, Science and Technology Studies, among others) and humanities and in nuclear energy research and policy will meet, exchange views and collaborate with civil society and other relevant stakeholders in order to:

- *Provide a societal perspective on the development and use of existing and new nuclear technologies,*
- *Provide an assessment of nuclear energy sustainability considering the entire life cycle of the current nuclear technologies,*
- *Provide a radically new economic model, based on the System of Provision (SoP), for the assessment of nuclear energy.*

The present deliverable provides recommendations for improving the ECOSENS life cycle sustainability assessment of energy technologies for the green transition, drawn from stakeholder feedback.

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Stakeholder demands for participatory technology assessment of energy sources for the green transition: *Recommendations to improve the ECOSENS methodology*

Deliverable 2.5 of the ECOSENS project

Summary

ECOSENS WP2 *Assessment of the sustainability of the whole cycle of nuclear power* constructed a life cycle assessment (LCA) tool to characterize and compare the sustainability of energy production sources in the context of the green transition [CONa,b,c,d]. A specific goal was to create a participative approach, one that could potentially be used by a broader-than-usual set of actors to systematically assess sustainability performance across the life cycle of energy technologies: old and new, fossil, renewable, and nuclear. The present deliverable contextualizes this effort in the history of technology assessment, showing that the ECOSENS implementation replayed classical tensions, but also that there is little precedent and there are no templates for participatory LCA. In this, ECOSENS WP2 provided innovative work.

This deliverable presents the extensive feedback and recommendations for participatory sustainability assessment drawn from three live or webinar stakeholder events/consultations: 1) elements of method [MAYa]; 2) desired scope and content [ZEL]; and – after a trial assessment – 3) detailed critique of approach, indicators, implementation and interpretation (presented for the first time in this report). Addressing broad-scale notions of societal decision making for sustainability, most recommendations remain aspirational, not directly applicable at the level of an LCA inventory/indicator approach, and/or requiring significant data, human and time resources. Nonetheless numerous actionable items are recorded, seeking more holistic, systemic (scenario-based) and integrative assessment, with clarified indicators measuring not only emissions but impacts and contributions to desired goals, for use by well-characterized and diverse stakeholder populations, and to result in transparent reporting. A set of lessons learned and further operational steps for improving the methodology are provided by the work package leader in Annex 5.

The ECOSENS team recognizes, with thanks, the high volunteer engagement in complex tasks by all the stakeholder participants, and their thoughtful intra-group cooperation during the feedback events.

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Acronyms

IAEA	International Atomic Energy Agency
INPRO	International Project on Innovative Nuclear Reactors and Fuel Cycles
IPCC	Intergovernmental Panel on Climate Change
JRC	Joint Research Centre of the European Commission
LCA	Life cycle assessment
NEA	Nuclear Energy Agency of the OECD
OECD	Organisation for Economic Co-Operation and Development
pTA	Participatory technology assessment
RES	Renewable energy sources
TA	Technology assessment
UNECE	United Nations Economic Commission for Europe
WP	Work Package

1. Introduction

Over the course of three project years, ECOSENS[1] Work Package (WP) 2 *Assessment of the sustainability of the whole cycle of nuclear power* constructed a specific variant of tools originally developed by the IAEA and JRC. Grounding this variant in fifty technical references, ECOSENS sought to provide a life cycle assessment (LCA) tool to characterize and compare the sustainability of energy production sources for the green transition [CONa,b,c,d]. A specific goal was to create a **participative** approach, one that could potentially be used by a broader-than-usual set of actors to systematically assess sustainability performance across the life cycle of energy technologies: old and new, fossil, renewable, and nuclear.

In a nutshell, the tool was itself constructed with workshop input (March 2023) from diverse civil society and academic experts [MAYa], and then trialed on line (Spring 2024) by 40 respondents evenly divided across technoscientific and social science fields. This was a **convenience sample** accessed through ECOSENS partner institutions, not presented as highly diverse or representative but available to perform a first in-depth test of the tools and online delivery platform. The web-based assessment interface included informative "fiches" on each of more than 60 indicators, providing data from the literature regarding the sustainability performance of the considered energy sources. The invited respondents used an online questionnaire form to record their individual, anonymous rating of the sustainability performance of each source (hydro; nuclear; natural gas; and intermittent renewables – solar and wind) on each indicator (using a Likert rating scale of 1-minimum to 5-maximum), consulting the associated fiches if they so chose. To avoid respondent fatigue the trial assessment task was presented over a number of weeks, with the survey broken into environmental, economic, and societal modules.[2]

The present deliverable was foreseen from proposal stage to compile recommendations for an improved methodology to assess sustainability. The recommendations are derived primarily from stakeholder[3] feedback on: the assessment approach; the tool, its components and their development; the quantified results obtained from the first trial application; and the interpretative report of those findings. It may be mentioned that the valence of feedback became more and more critical across the stages of WP2 deployment:

- The March 2023 development workshop [MAYa] saw 15 civil society and academic stakeholders highly engaged and cooperating face-to-face on complex work-sheet/discussion tasks. They gave guidance for the overall approach to participative assessment including high-level goals and some features of indicators. Importantly, they reflected on sustainability assessment well beyond the boundaries of LCA.
- At the ECOSENS Scientific Event of August 2023 [ZEL], four members of a diverse stakeholder panel (some carry-overs from the March workshop, some new) voiced

[1] ECOSENS: Economic and Social Considerations for the Future of Nuclear Energy in Society, 2022-25.

[2] Full and detailed reports of tool construction, trial assessment process and findings are found in [CONa,b,c,d] and [MAYa]. This content will not be repeated in the present report.

[3] We will not provide a limitative definition in this report of "stakeholder". No such definition was provided in the ECOSENS project as a whole. We tend to support the definition developed under the OECD NEA FSC: "any actor - institution, group or individual - who has an interest or role to play" [FSC] in the processes studied or managed. We also highlight, with our colleagues in ECOSENS, the importance of civil society representatives and citizens as stakeholder-actors. Of note, no contrast is made or intended here between "experts" and "stakeholders," as all of the latter may be considered topical specialists in their own domains.

sterner cautions regarding the general assessment approach, calling for a scenario-based technique.

- Finally, at a March 2025 webinar (reported in the present deliverable) a mainly new set of 15-17 diverse stakeholders, also highly engaged in a cooperative review of selected trial assessment outcomes, delivered extremely critical remarks. Most members of this final panel had not personally road-tested the LCA tool, but they had prepared for the discussion by examining and/or attentively listening to a detailed summary presentation of findings on 8 salient indicators, and some had examined the full report of trial results [CONd]. To briefly summarize their feedback, some questioned the *sources and models* underlying the informative fiches. Some disputed the use of *polling*[4] whether to perform such technical indicator-based assessment or to engage stakeholders and obtain their reasoned views. Many questioned the *formulation of the indicators* (although a proportion of these critiques probably stemmed from the abbreviated character of summary materials). Some surmised from findings that the trial *sample* was biased towards pro-nuclear actors. Finally, some questioned the *interpretation* of the quantified results, viewing the report as biased toward the promotion of nuclear technology.

Each of these three consultations[5] yielded recommendations to improve the methodology, its transparency, useability and validity; specific quotes and details will be given in Section 4 and annexes of the present document. These materials were presented and discussed at the final project meeting and conference hosted by partner POLIMI in Milano (Sept. 2025) and reflect WP3 advice.

In preparing this deliverable, we looked back at the 60-year reflexive literature of **technology assessment (TA)**, the umbrella under which one may consider that life cycle sustainability assessment is conducted. We felt it useful to understand the purposes for which TA has been developed and the sorts of tools that are considered fit for purpose. With such perspective, we felt we could contextualize and weigh the critiques and recommendations received by ECOSENS. Of great interest, we found that *the possibility of making technology assessment truly participatory* has been a central stake of the field since the first years of its formal development. Furthermore, the occult pressure of dominant political framings, the challenges of integrating quantitative and qualitative input and of achieving multidisciplinarity, were all voiced and elaborated from very early days. We found that the general critiques voiced during our ECOSENS exercises echo such observations formulated already fifty years ago and more. One might then conclude that WP2's work despite its aspects of rigor was not up to the state of the art; or, one could equally surmise that such critiques reflect **fundamental tensions of the field, not easily evacuated.**

[4] *Polling* is a systematic method of collecting votes or data (opinions, judgments) from a specific population using standardized questions and procedures, typically using a rating scale (rather than e.g. open questions as often seen in *surveys*).

[5] For the record, while just three are considered in this deliverable, five stakeholder feedback consultations of varying depth were conducted in total by ECOSENS WP2. The two events excluded from our analysis here are a June 2023 webinar on "Clarifying non-linear assumptions about energy demand to 2050" [FOU] and a non-reported follow-up workshop on the same topic at the ECOSENS Scientific Event (Dessel, August 2023). The actual trial run of the proposed sustainability assessment method [CONd] constitutes a sixth consultation, although bounded mainly to a convenience sample of specialist participants accessible through ECOSENS partner institutions without direct representation of civil society stakeholders.

This introduction briefly presents the ambition of ECOSENS WP2 *Assessment of the sustainability of the whole cycle of nuclear power*. It contextualizes this ambition first by mentioning a recent major preceding European-level energy LCA endeavor. Then the report goes on (Section 2) to reference some foundational discourses (and critiques) of TA, particularly from the point of view of its traditional weakness: achieving explicit integration of diverse perspectives, societal views and values. This literature review concentrates on the first quarter century of TA development. It is not intended to fully represent the history of TA, nor to account for the iterative development of concepts and techniques in response to critiques, but only to give background. Section 3 presents a small handful of more recent references deploying features of LCA (as a branch of TA) to suggest that ECOSENS' ambition to create a participatory LCA may be considered a significant innovation. Section 4 presents structured (if general, high-level or aspirational) methodological recommendations gathered from stakeholder consultation events and ECOSENS researchers. After summary reflections and conclusions in Section 5, several annexes present useful detail: 1) critical remarks from an Advisory Board member; 2 & 3) stakeholder verbatims not previously published in ECOSENS documentation; 4) suggested reading to identify participatory TA techniques; and 5) deliverable review reflections by the leader of WP2, main author of the ECOSENS LCA approach. The latter Annex 5 highlights the recommendations viewed as most immediately operational for near-term improvement of the methodology.

1.1. The ECOSENS ambition: reflect societal preferences in a systematic comparison of energy sources

Why sustainability assessment of energy technologies in ECOSENS? Why the participation of stakeholders in the ECOSENS assessment?

> "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." [CONc, p5]

This was the setting and the ambition of ECOSENS WP2. Under the lead authorship and motor force of M. Constantin from Romania's national Institute for Nuclear Research (ICN RATEN), WP2 produced a detailed investigation of the role of nuclear power in the future energy market [CONa] as well as the narrative description of four scenarios for a climate-neutral energy sector in Europe combining new nuclear technologies and variable renewables [CONb; FOU]. Most significantly, ECOSENS WP2 attempted to **design and conduct a participative**

assessment of the sustainability performance of key energy technologies driving the green transition: intermittent renewables (wind and solar), hydropower, nuclear power, natural gas [CONc,d; MAYa].

To seek a participative dimension in a structured and precise assessment is in keeping with the European Union's avowed vision of the green transition:

> "The involvement and commitment of the public and of all stakeholders is crucial to the success of the European Green Deal. Recent political events show that game-changing policies only work if citizens are fully involved in designing them. People are concerned about jobs, heating their homes and making ends meet, and EU institutions should engage with them if the Green Deal is to succeed and deliver lasting change. Citizens are and should remain a driving force of the transition."

This vision was quoted[6] in the European Environment Agency's briefing presenting "key insights from sustainability studies regarding public participation and [explaining] why a thoughtful approach to participation is particularly needed for sustainability transitions (…,) insights [to] inspire participatory approaches in governance processes that, until now, have focused more on scientific, technical and administrative aspects." [EEA p3]

1.2. A recent European precursor: Justifying life cycle sustainability assessment

The ECOSENS trial assessment completed in 2024 was by no means a "first of a kind" approach to sustainability assessment for the European energy transition. Nor did it have the ambition or the wherewithal to attain the complexity of a well-resourced in-depth assessment. An example for comparison is the 2021 UNECE report entitled "Carbon Neutrality in the UNECE Region: Integrated Life-cycle Assessment of Electricity Sources" [UNECE]. The endeavor explained and justified an economic policy need for life cycle assessment (LCA) in the context of massive electrification to fulfil IPCC mitigation scenarios; for example:

> "Life cycle assessment allows the evaluation of a product over its life cycle, and across a wide range of environmental indicators (…). This method was chosen to provide a fair report on the environmental profiles of various energy technologies at parity to develop effective and fair policies to attract financing. (…) The results show that all [energy] technologies impact the environment and subsequently have economic and social implications." [UNECE p6]

The complex systemic LCA was presented in 108 pages with 60 figures, 32 tables, 4 technical annexes, and 147 references (models, databases, preceding studies of defined scope, etc.). The "cradle to grave" analysis considered 22 utility-scale technologies' potential environmental impacts on human health and ecosystems, and their resource requirements. The effort aimed to update a previous assessment (2016) with fresh data; explore in detail the features of each technology responsible for impacts; identify the reasons for variations in impact; and cross-compare technologies. The report included examination of 12 world regions to identify the environmental cost of delivering one kWh of electricity to the grid, on a global average, for 2020. Of interest, this publication acknowledged that study resource limitations

[6] With no identifiable reference to European publications; [EEA p4].

prevented: full examination of uncertainty; refinement and systematization of source data; or detailed system modelling to include storage technologies.[7],[8]

The study furthermore recognized the boundaries of LCA:

> "Finally, many potential impacts of energy technologies are known but unquantifiable through a strict LCA approach. These aspects have been mentioned in technology-specific sections, they include **acceptance, costs, aesthetic impacts, or biodiversity threats**. Risks are excluded from LCA, as LCA only assess routine operations of a system. Risk analysis is a well-developed discipline that can inform decision-making with, in our case, analysing accidents from energy supply chains." [UNECE, p63; emphasis added]

The ECOSENS approach described in detail in [CONc; MAYa] did not attempt to replicate this extensive scale of study. While ECOSENS followed the principles of the [ISO 14040] standard for LCA, and was grounded in existing elaborated methodologies [KUZ; IAEA; JRC], a specific differentiating aspect of the ECOSENS work was the commitment to seek broad-based stakeholder feedback across all methodological stages of an LCA exercise.

As it unfolded, ECOSENS both responded to a democratic ideal, and perhaps naively replayed some of the historic attempts at reconciling technocracy and democracy [BER].

[7] We acknowledge that during the ECOSENS webinar of March 2025, an NGO stakeholder participant criticized the use by [UNECE] of "grey literature" provided by the World Nuclear Association (WNA), judged insufficiently transparent or reliable; this critique was extended to the ECOSENS data fiches to the extent they drew on "WNA consultation" data. Nonetheless, examining this claim an Advisory Board reviewer states that such literature can be considered an acceptable source to the extent that data are "triangulated" with other sources.

[8] A reviewer of this deliverable highlights a critique discussed during two ECOSENS stakeholder consultations ([ZEL], and see Annex 3 of the present document): [UNECE] "does not take into account the limited role that nuclear energy would play, if it were to play a role in 2050. This is based on (not explicitly assessed) presumptions about an increase of that role, but even in the physically impossible case of a doubling of nuclear capacity in 2050, nuclear energy provides less than 4% of greenhouse gas reductions (based on the OECD NEA scenario studies based on the WNA Harmony scenario). This includes less than 6% of energy provision, while the sustainable technologies with which comparison is made are in that case covering 80% or more of the energy provision."

2. Participatory technology assessment: An old question, persistent tensions

Considering LCA as a variety of technology assessment (TA), this chapter presents a brief historical glimpse of the emergence of TA (in the United States) to grasp the spirit in which TA was developed and institutionalized, and in particular to highlight the early concern with integrating public participation. For many actors in TA's history, involvement of societal stakeholders in TA is essentially a given because it emerges as a tool to inform societal decisions on innovation. Nonetheless, our brief investigation found statements by empowered actors setting out objectives for TA centered more on fostering economic growth than on eliciting and incorporating societal preferences. In this discussion we will simply identify some tensions present in the field since its inception, and which were reproduced in the ECOSENS exercise.

2.1. Emergence of TA: Aims and definitions

Technology assessment is a broad, often policy-oriented process that examines the potential impacts (environmental, economic, social, ethical) of technolog(ies) before, during, or after deployment[9]. Sustainability assessment (or usually, life cycle sustainability assessment) is a methodological framework to acquire quantitative, systematic evidence about the sustainability performance of a product, technology, or technological system throughout its life cycle. In this way LCA can provide a suite of tools and a particular profile of data to a larger multimodal assessment process.

Today we tend to understand the *co-production* of science, technology, and societal postures and decisions (or "knowledge and social order") in the light of [JAS]'s seminal 1996 formulation, but their entanglement has been explored by many (see e.g. [ELL]). As for technology assessment precisely, [SAD] traces the premises of institutionalized TA to a 1929 federal US report providing a critical analysis of economic stability and instability, and a 1937 follow-up report entitled "*Technological Trends and National Policy*" – 450,000 words written by social scientists and technical experts, its opening section entitled "Social Aspects of Technology". [SAD] ratifies [INO, p619]'s view that the broadly disseminated 1937 report "must have made US government officials, and to some extent the public, recognize that evaluation and prediction of technology and its effects are necessary for the welfare of society."

The term "technology assessment" came into (legislative) vocabulary in 1967 when the United States Congress sought a "new form of policy analysis capable of dealing with the various pervasive – and often negative – effects of technological innovations which have a high diffusion potential in the productive sectors of the national economy." [WAD pp3-4] TA was viewed as an "extension of the operational research/systems analysis/futures research family of thinking"[10] (also arising in that decade), apt to enlighten and support societal decision making.

[9] This definition and discussion are inspired by our reading of [WAD], a 1984 UNESCO review by sharp-sighted practitioners and published for development workers; and by digging directly into some of the many original and secondary sources referenced therein.

[10] [KEN] in [WYN].

In the conceptual and methodological development of TA much thought and appropriate caveats were given as to the robustness of projections and prediction; it is nonetheless clear that TA was concerned with both the present and the future well-being of society. The notion of *sustainability* was formalized later, in the 1987 report "Our Common Future"[11] [WCED]; thus, sustainability as such was not referenced.

The term "technology assessment" is generally attributed to US Congressman E.Q. Daddario, a chair of the Congressional Subcommittee on Science, Research and Development. Daddario sponsored the 1967 bill H.R. 6698 establishing a Technology Assessment Board and later led the Office of Technology Assessment (OTA, created in 1972 and abolished in 1995) which provided advice to the Congress. Daddario wrote a valuable 1969 two-page reflection on TA (quoted in extenso in [CRS]):

> "Technology Assessment is a form of policy research which provides a balanced appraisal to the policymaker. Ideally, it is a system to ask the right questions and obtain correct and timely answers. It identifies policy issues, assesses the impact of alternative courses of action and presents findings. It is a method of analysis that systematically appraises the nature, significance, status, and merit of a technological program. The method may well vary from case to case (…). Technology Assessment is designed to uncover three types of consequences—desirable, undesirable, and uncertain. (…)
>
> "Technology means change—change to the natural environment, change in personal habits and behavior, change in social and economic patterns, and not infrequently, change in the legal and political processes. While many of these changes are beneficial, many are disruptive and dislocative. They change situations more rapidly than the pace at which individuals can adjust. The well-known cultural lag finds its logical beginnings in the phenomena. Assessment of the risks is a necessary concomitant to assessment of the benefits. (…)
>
> "To assess technology one has to establish cause and effect relationships from the action or project source to the locale of consequences. A direct or immediate effect is easy to spot and assess. The direct effects, in turn, will cause other consequences—indirect or derivative effects. As the scope of assessment moves outward in time the derivative effects become the result of many causes and not of one specific technological change (…). The function of technology assessment is to identify all of these [impacts and trends]— both short-term and long range. The emphasis though will be on the short-term impacts that can be measured by natural science parameters. That is, the focus of Technology Assessment will be on those consequences that can be predicted with a useful degree of probability. Possible

[11] Recall the place of civil society and public participation in achieving sustainability, from the introduction by chair G.H. Brundtland of the eponymous report: "We call for a common endeavour and for new norms of behaviour at all levels and in the interests of all. The changes in attitudes, in social values, and in aspirations that the report urges will depend on vast campaigns of education, debate and public participation. To this end, we appeal to 'citizens' groups, to non governmental organizations, to educational institutions, and to the scientific community. They have all played indispensable roles in the creation of public awareness and political change in the past. They will play a crucial part in putting the world onto sustainable development paths, in laying the groundwork for Our Common Future" [WCED p9].

> changes in values, attitudes, or motivations are important but not easily predicted. These changes are usually long term and fall beyond the primary focus of Technology Assessment. Therefore, because of their slow evolution, present human values and political motivations will serve as the frame of reference for purposes of measurement and appraisal." [USC pp12-14] in [CRS pp45-46]

Thus the formal inception of TA was marked by recognition that technologies and assessments alike are embedded in their time and place. While innovation may move quickly, slower-moving "values, attitudes, or motivations" were viewed as the necessary reference points when assessing and evaluating technology impacts.

The aim for an assessment process supporting judgments that could serve society now and for future years can be found in many statements. These can be read too as implicit or explicit justifications for stakeholder input into TA. For instance, according to e.g. [ARM], definitions of TA (seen as inherently and necessarily multidisciplinary) rely on two assumptions. Firstly, the implementation of innovative technology or expansion of conventional technology is – or should be – a conscious societal choice; and secondly, technology itself is generally not inherently harmful but its management must consciously be conducted for the long-range interest of society.

But who is to furnish the reading of the societal context and of present and long-range interests? Who is to make "hard" and "soft"[12] references and data explicit, and how? Can technology assessors of any stripe escape in neutral objectivity from what was understood early on to be a site of political struggle?

2.2. Public participation in TA: can it "become real"?

Public input to technology assessment was strongly expected by originators of the United States' OTA.

> "Soon after the agency's creation [BRO], one of the conceptual architects of OTA, put forth the question: 'What is the appropriate role of the public in TA?' During the initial hearings about OTA [1972] there was little opposition to the belief that participation was an important aspect of TA because it **provided a diverse set of perspectives and improved public trust in the process**. As Sen. Warren Magnuson (D-WA) stated: 'We need more intimate public participation in this decision-making enterprise, particularly at the regional, state and local level, so as to gain a better insight as to what people want and don't want' [OTA p88]. However, OTA never really was successful at consistently and meaningfully incorporating participatory methods that engaged with and incorporated perspectives from heterogeneous groups of lay citizens into TA practice…" [SAD p18; emphasis added]

… A requirement that was already perceived in 1954 by [ELL] as "crucial for democratic control and oversight of technoscience." [SAD p18]

It must not be thought that involved actors were unanimously on the same page regarding the why, the how, or indeed the how much of public participation in TA. As [DIC] pointed out, a 1969 [NAS] report put forward that participation should be "restricted to 'well-defined

[12] This polarity according to [ARM] covers technologies which themselves can be "hard" or "soft". It also indicates data of precise quantified measurement vs. "imponderables" [WHI], including culturally determined factors, for which adequate tools and concepts were comparably rare in the first decades of technology assessment [WAD].

channels,' while 'mechanisms should also be provided to filter out truly frivolous or irresponsible claims' – a suggestion that left open the political question of who was to determine the criteria for frivolity or irresponsibility."

Meaningful, impactful citizen or civil society participation was nonetheless a foundational concern in technology assessment from its inception. A symposium organized in 1973 by the National Academy of Public Administration's Standing Committee on Environmental and Resource Management focused on public participation in TA. One paper gave a simultaneously encouraging and scathing reading of the situation, in language that seems very contemporary:

> "In an institutional or structural sense, the issue of public participation in technology assessment is not really new. It is part of the enduring question of the division of power in society; how is it shaped, shared, and used? Who decides? Is public participation in technology assessment just another performance being staged in the theater of political make-believe?
>
> "(…) Public participation in the decision processes of our common life may be at a greater level than ever before. It may just be that our expectations are higher than they ever have been, too! Even with these optimistic comments, is it possible that public participation in technology assessment is basically a sham and a fraud? If it isn't, why then is it that citizens and the public are always asked to choose among alternatives that others have designed and presented to them? Why is it that citizens are not asked to specify the world they want and the alternatives which they desire?
>
> "Until this question can be honorably answered by managers and professionals, then I believe that the fundamental issues and concerns underlying true public participation will not be addressed. If the concept of public participation in technology assessment is real, it means that bureaucrats and business managers are not going to be able to allocate resources with the freedom and abandon they have heretofore had. Public participation implies a profound involvement in determining what resources are available to the *covenantal community* [of well-being], and to whom those resources are available. The ultimate question is whether those who have been accustomed to making the key decisions, the bureaucrats and the managers, are willing to hold themselves accountable to the citizenry and particularly to the covenantal community rather than to the polity or the business corporation." [DIX; original emphasis]

Many thoughts arise in reading this impassioned diagnosis in 2025, 52 years after its declaration. Among these, in no particular order: Blair Seaborn, chair of the Canadian Environmental Assessment Panel on Nuclear Fuel Waste Management and Disposal Concept (1989-98) was onto something when he extracted from public hearings that "*a choice of one is not a choice*"[13]; the notion of "performative" actions, and the growth of demand for public participation, reflect perhaps longer trends than presentism would have it; the demand indeed is gradually better supported by legislation stemming from e.g. the Aarhus Convention. There is indeed greater focus on deliberative governance to be seen today; e.g. the OECD Public Governance Directorate on open government in 2021 identified some 600 examples of participatory policy applications, "of which over 80 were implemented in the last two years alone", a trend heightened by the technological means provided by internet and acculturation to such means in the COVID-19 context [PUB]. Only one of those applications, however,

[13] Personal communication, Port Hope, Canada, October 2002.

concerned some species of technology assessment (a climate change and energy transition event held in Australia in 2007 [EDW]) and none concerned more precisely LCA.

Also deeply involved in early efforts to achieve citizen input to technology assessment was Sherry R. Arnstein, present at the same 1973 seminar with a methodological proposal. She had already published in 1969 her well-known "ladder of public participation" in decision making [ARN], derived from co-planning in an urban development setting, and depicting 8 rungs categorized from non participation to tokenism to citizen power. The ladder is very largely cited in planning and policy making, and particularly in ECOSENS topical domains such as nuclear infrastructure siting. An interesting 1995 paper from the International Institute for Environment and Development [BAS], translates the ladder (from a pertinent rung) into a sustainable development strategic context, noting a typical rupture between rungs 1-5 and the rarely achieved level 6.

> "A Typology of Participation in Policy Processes and Planning
>
> 1. Participants listening only (e.g. receiving information from a government PR campaign or open database).
> 2. Participants listening and giving information (e.g. through public inquiries, media activities, 'hot-lines').
> 3. Participants being consulted (e.g. through working groups and meetings held to discuss policy).
> 4. Participation in analysis and agenda-setting (e.g. through multistakeholder groups, round tables and commissions).
> 5. Participation in reaching consensus on the main strategy elements (e.g. through national round tables, parliamentary/select committees, and conflict mediation).
> 6. Participants involved in decision-making on the policy, strategy or its components.
>
> At each level, participation may be narrow (few actors); or broad (covering all major groups as well as government)." [BAS, Table 3, p50]

[BAS p.54] also articulated "key political dilemmas" likely to arise with higher degrees of participation. While this work did not bear specifically on technology assessment, but rather on sustainable development strategy building (including technological elements), it is useful to witness continuity in the concern for making public participation become real. The typology also lends insight into the relatively narrow array of tools drawn on (at least by this particular international community) in the mid-1990s to systematically gather multiple perspectives. In the ECOSENS contribution to green transition policy and planning, the WP2 sustainability assessment exercise (methodological workshop [MAYa] and online trial assessment exercise) likely corresponds to rungs 3-4 of this typology.

2.3. Further tensions: barriers to participation; validity and validation of TA; interdisciplinary challenges

Further tensions that remain present today, and which appeared during the ECOSENS WP2 stakeholder feedback, were discussed too starting half a century ago. These include diverse material or conceptual barriers; issues of validity and reliability of TA methods and data; and achieving interdisciplinarity.

The fundamental **need to ensure meaningful participation, and simultaneous obstacles** of different orders to achieving it, were cogently reviewed by [WAD]. These include **representativeness; conceptual unfamiliarity; cost and commitment; levels of education and awareness; methodological gaps.**

> "Because TA is meant to be a method to ensure that the interests of various social groupings are reflected and addressed in the development of technology, much attention has been given to public participation in the TA process [POR; MAR]. While there have been efforts to incorporate such public inputs into all stages of the TA process, typically, these have been limited to initiating contacts with representatives of concerned public interest and stakeholder groups, and to seeking expert advice. [ARM p124] note that useful public input is difficult to obtain, partly because the inherent 'futuristic nature of TA involves situations for which experience in the present offers little or no analogy'.
>
> "While a large number of approaches and techniques have been suggested to solicit public participation - interviews, representation, use of media, questionnaires, participatory assessment, conferences, role playing, etc. - the reality of the matter is that to accomplish such a goal satisfactorily is often expensive, time-consuming and requires a considerable commitment on the part of the assessors." [WAD p44]

[BER] also forcefully argues the atrophy of citizen participation in TA in light of severe underfunding and the professionalization of assessments led by TA institutions:

> "A commitment to democratic principles should make it intolerable to pretend that if the voice of the poor is excluded, because they cannot afford to travel to make a presentation, for example, and then only the professionals or wealthy are actually heard, that somehow a 'neutral' or 'balanced' assessment is likely to result. (…) [A]ctivities will be of lesser quality if citizen participation is not assured." [BER p174]

Then, the issues of conceptual familiarity, education and awareness were recognized as potentially inhibiting broad participation:

> "One has also to face the problem of low educational levels (…) [as] proposed approaches presume a certain level of education and awareness on the part of the public. However, it could also be argued that the level of awareness does exist (…) but that the means of assessing and articulating public opinion need to be developed." [WAD p44]

Another issue concerns **validity, and thus validation, of TA methods and outputs**. The backward glance confirms that this issue was not viewed as specific to TA, but reflected larger problems encountered in the evaluation of diverse and qualitative data. The **potential for inherent biases** in both TA methods and evaluations was identified from the outset:

> "As [MAR] notes, there is considerable debate about what constitutes validation in TA, reflecting a similar debate in the larger sphere of the social sciences. The key question here is how one goes about ensuring that the results of a TA are indeed accurate, reliable and objective. This involves examining the internal and external validities of the measures used in the assessment (…) [and] their completeness (…). There have been measures developed for validity testing in the social sciences which can be applied in the case of TA. However, it is still debatable as to whether these validations might not be serving to further obscure what some believe to be the implicit value-

> laden and interest-specific nature of TA theory and methodology. The problem of validation must therefore examine critically the fundamental criteria in an assessment in terms of the political and value components, and it is at this level that the problem of validation becomes controversial (…).” [WAD p42]

A particular aspect calling for attention is **construct validity** (congruence between the sometimes abstract object of measurement and the data indicators), that is, the **fitness-for-purpose** of an approach. In the first decades of its large development, a broad panorama of methods was accepted for TA, with emphasis on the value in novel assessment contexts of bottom-up approaches “derived from the situation and problems at hand.” [WAD p39] At the same time, those authors paradoxically decried the fact that practitioners ignored the ample research and formalizations emerging during the rapid institutionalization of TA, preferring approaches drawn from their own “intuition” and moreover, in a “distressing trend”, displaying a “tendency to try to quantify even those variables that are not quantifiable through elaborate procedures of coding, ranking and the like”. [WAD p38] This observation rejoins historian [WHI]’s underscoring of the presence of “imponderables” in societal views on technology that cannot be appropriately measured by quantitative approaches.

We may push forward to look at underlying cultural factors leading to disputable choices of method. [WYN p108] questions a “founding canon of TA, namely that knowledge begets social consensus, and that where there exists no social consensus as to the evaluative framework by which society will assess its technology, then it can be objectively created by gathering and disseminating more social data.” He further argues that the use of e.g. cost-benefit analysis “serves to reduce basic conflict and divergence to a shallow materialistic illusion (…) [T]he framework of data-collection and analysis is heavily constrained by some fairly important political predispositions and assumptions, and (…) the route from analysis to synthesis is already largely pre-determined!” [p152]

Finally, the mixed quantitative and qualitative domains represented in the objects of technology assessment imply the need for **interdisciplinarity**. This too is a contemporary problem encountered in HORIZON Europe research inter alia, perceptively recognized and unsolved in TA half a century ago.

> “The conduct of technology assessment is an interdisciplinary exercise involving specialists from various fields and addressing a range of variables both technical and non-technical. It therefore encounters the problems that are typically associated with interdisciplinarity. The problem is at least in part an epistemological one of having to deal with the different "world views" of different disciplines, but it is also a practical problem in terms of the interactions between team members in an assessment. [MAR] describes several problems associated with interdisciplinarity in TA.” [WAD p41]

[MAR]’s discussion considered the **differential in disciplinary assumptions and standards; willingness to speculate; and attitudes toward data; as well as observances of scientific pecking order**. [WAD] continue on the methodological plane to recognize that the point of interdisciplinarity is not to combine heterogeneous approaches, but to achieve a holistic grasp of the object of assessment:

> “The problem of interdisciplinarity is, over and above the level of interactions among researchers from different disciplines, a problem of integration of disciplines into a truly interdisciplinary conceptual framework accompanied by appropriate methodologies. Such a framework has to be more than a simple combination of

different disciplines which still maintains the traditional disciplinary boundaries. It needs to synthesise and integrate contributions from different disciplines into conceptual categories that are more suited to a holistic interpretation of the subject of study." [WAD p41]

3. Participatory life cycle analysis? Recent parallels

The look backward suggests that issues keenly felt today in creating participatory technology assessment, or more generally in attempting to integrate stakeholder input and preferences in policy-making around technological choices, have accompanied the emergence and development of TA in the last 50 years and more.

A valuable reference closer to our time (2010), thoughtfully examining such issues and consolidating the advanced elaborations of "pTA" (participatory TA) that have emerged more recently, is [SCL]. This work however makes no reference to *life cycle sustainability assessment*, the target of ECOSENS WP2. Indeed in our bibliographic research we found no older references to participation in LCA.

Below we briefly present recent references that may characterize different levels of participation in developing tools or models for application within LCA. Strikingly, these do not appear to seek to include civil society.

3.1. EUCalc and Openmod: user requirements and inclusivity

An example of a potentially adequate reference dates from a more recent 2016-2019 period. The European project EUCalc did not conduct an LCA exercise as such but developed models and tools that could take their place within a participative LCA. EUCalc developed a user-friendly toolkit "to compare low-carbon transformation pathways on the European and member state scale" and thus enable informed stakeholder participation in the "energy, emissions and resources debate". The project developed "a novel and transparent open source model combined with a Transition Pathways Explorer (TPE), an online tool providing instant results from the EUCalc model runs. With the TPE, European and national policy-makers, businesses, NGOs, innovators, and investors will be able to create (online and in real-time) their own pathways and compare them to other integrated pathways." [MWA p5] The project used two stakeholder workshops, gathering 15 stakeholders from European policy roles, civil society organizations and industry in a structured two-part consultation to identify user requirements for the toolkit. These requirements were methodological, substantive, and/or purpose-related. Sectoral workshops were then to be held to agree further normative aspects ("ambition levels of respective levers"; p10).

Another interesting reference, which again represents only a particular step or component within LCA, is provided by the Openmod open energy modeling initiative, which since 2014 has pursued "ways to expand the inclusiveness and impact of open energy modelling without compromising technical rigour." As "one of the largest grassroots initiatives in the energy planning field, we exchange ideas and source code, lobby for policy support for open projects, actively share data, results, and know-how, and seek community-wide solutions to overarching challenges". The initiative recognizes that "addressing the complex challenges of climate mitigation and adaptation, alongside the wicked problems inherent in energy systems, demands transdisciplinary and co-creative modelling support." The 2025 Openmod workshop hosted by the KTH Division of Energy Systems welcomed 60 participants, called for contributions that:

> "(…) may include describing tools, methods, and experiences that foster broader participation, such as model comparison, benchmarking, and model coupling to integrate insights from diverse disciplinary perspectives. Inclusiveness, in this context,

extends to: groups with physical barriers to modelling participation; practitioners with tangential expertise who may be users of model outcomes; new modellers, particularly from low- and middle-income countries (LMICs) and underrepresented regions; stakeholders across sectors, including academia, industry, and government." [14]

Thus, while civil society is not explicitly mentioned in the call or the initiative's Manifesto[15], the open remit suggests that the annual workshop could accommodate reflection on how to integrate diverse stakeholder input to open-source models and how to facilitate non-modeler use of energy models and outputs during the interpretation phase of an LCA exercise.

3.2. The Joint Research Centre assessment: a significant reference

A major LCA exercise that cannot be forgotten in this report is the one conducted by the Joint Research Centre of the European Commission and published in 2021. "*Technical assessment of nuclear energy with respect to the 'do no significant harm' criteria of Regulation (EU) 2020/852 ('Taxonomy Regulation')*" [JRC] is significant for several reasons, although it does not provide an example of participative LCA.

One reason regards its completion in the context of European Union regulatory investigations of whether an economic activity (here, nuclear energy) qualifies as environmentally sustainable so as to show whether economic investment in that activity in turn qualifies as sustainable. The approach and some related regulatory texts have been disputed by e.g. Greenpeace and Austria[16] including on grounds of insufficient stakeholder participation at various phases. We will not detail this thought-provoking context in this deliverable, although we note that the (expert) interpretation step of this LCA resulted in a recommendation that nuclear energy be included in the taxonomy of sustainable activities, recommendation taken up by the EC.

Another reason to include this reference in the present report is that many environmental indicators selected by [JRC] were judged by [CONa] to be useful to the ECOSENS LCA approach under development, and the life cycle scope from that study also was adopted. Moreover, ECOSENS combined those aspects of the [JRC] LCA with other aspects selected from MCDA-KIND [IAEA; CONa], and proposed this combined method as a decision-in-principle to the March 2023 ECOSENS stakeholder workshop. The choice was examined and ratified by participants [MAYa].

[JRC] provides a short history of LCA, sourcing it in the 1960s to concerns about the environmental impacts of a particular consumer product packaging and the goal of identifying alternatives. The approach developed within private industry to compare energy and environmental resources requirements, emissions and waste generation across the value chain of given products. In the 1970s a theoretical framework was codified. In Europe life cycle measures were broadly integrated into policy with the establishment of the Directorate-

[14] https://forum.openmod.org/t/openmod-2025-announcement-concept-and-agenda-25-26-march-2025/5060
[15] https://www.openmod-initiative.org/manifesto.html
[16] See for information two cases before the courts: https://climatecasechart.com/non-us-case/greenpeace-and-others-v-commission/; https://climatecasechart.com/non-us-case/austria-v-european-commission/; and dismissal of the latter case: https://agenparl.eu/2025/09/10/press-release-113-25-judgment-of-the-general-court-in-case-t-625-22-austria-v-commission/#google_vignette, dismissal which will be appealed.

General for the Environment. International standardization emerged in the 1990s and throughout the 2000s there was development of global and regional platforms to promote accessibility and use of quality-assured life cycle data, methods and assessments. [JRC] also briefly reviews the limitations of the latter iteratively-developed resources to assess products and technology systems in an innovation stage. They note also that LCA is traditionally used only to assess and compare environmental impacts, excluding e.g. workplace effects (although human health is used as one target within environmental effects). We note that life cycle socio-economic impact assessment can be part of a holistic approach but it is considered under-operationalized at this time and in need of elaboration. [e.g. MAYb]

To what extent was stakeholder or moreover civil society participation integrated into the [JRC] taxonomy study? "If not enough data are available, assumptions, engineering estimates, and decisions need to be made based on the stakeholders [sic] values." [JRC p23] Few references are found however in the study report regarding the collection of such "stakeholders values" and in any case civil society as a stakeholder group does not appear to be prioritized in those few citations. For example, [JRC p33] cites a review of data for the projected evolution of energy technology shares in Europe; the ASSET project contacted 100 stakeholders but the participation list shows these were uniformly from industry. The framing of the notion of "stakeholder" in [JRC]'s large LCA appears to be relatively narrow. Search hits on the term through the report often show "stakeholder" to be associated with the qualifier "relevant" (thus reducing scope), and yield such statements as e.g. nuclear waste management stakeholders (those with "rights and responsibilities") to be "operators, waste management agencies, regulatory authorities, and the State". [JRC p197]

Interestingly, for the quantification of radiation effects on human health [JRC] references a model containing a measure of DALY (Disability-adjusted life years) from [FRI]. This 2000 methodological paper itself relies on a 1998 study that puts forth the objective of integrating the "valuesphere" alongside the "technosphere and ecosphere" in LCA, and uses attitudinal categories drawn from Marie Douglas' Cultural Theory (e.g. egalitarianism vs. individualism) to characterize preferred policy approaches, pertinent time horizons, etc. As such, one may surmise that under such a framework direct stakeholder consultation is unneeded, as Cultural Theory [DOU; THO] would provide a sort of social data inventory comparable to empirical inventories of emissions data, etc.

To be fair, failing to seek direct stakeholder input on the data and models of LCA ([JRC] cites and integrates some 150 studies) might be justified under the settled methodological notion that LCA does not state which alternative is best, but simply compares performances on given indicators. In this perspective, broad stakeholder input (preferences) could be sought at interpretation stage to weigh the observed performances in view of decision making. The [JRC] report appears in general to delegate such consultation to Member States and legislated processes[17], e.g. the review phase of Environmental Impact Assessment for new nuclear plant projects: "Current legislation regulates the contents of the assessment, and it also contains provisions to ensure a comprehensive participation in the process of all stakeholders involved,

[17] Note that according to the suits brought by Greenpeace and Austria (see footnote 16) the required procedures for consultation, using the vehicle of the Platform on Sustainable Finance (which "brings together the best expertise on sustainability, from industry, academia, civil society and the financial industry" https://finance.ec.europa.eu/sustainable-finance/overview-sustainable-finance/platform-sustainable-finance_en), were not properly executed in the case of drawing conclusions from [JRC] itself, and the Platform viewpoints were not incorporated in the final taxonomy decision by the EC.

including citizens and neighbouring countries." [JRC p144] Later in the document a list of pertinent stakeholders is extended beyond technical and state actors to "Potential host communities: [who] accept or reject the proposed facility; interact with regulators and policy-makers; negotiate with waste management organizations for the benefit of the local community." [JRC p250, based on FSC] This latter role does not appear to foster participation in the conduct or interpretation of any LCA (nor even, on the face of the quote, any EIA; indeed it hearkens back to the 1973 observation by [DIX] and others we have quoted, that citizens – here "potential host communities" – appear to be excluded from assessing technology options but are instead characterized as accepting or rejecting proposed facilities).

All in all then, **it is not insignificant that the ECOSENS project sought to integrate diverse stakeholder feedback at several stages of an LCA** to compare the sustainability performance of energy production sources considered for the European green transition. Against the background of LCA references available to our web-based literature search conducted in Summer/Fall 2025, the ECOSENS ambition and approach indeed appear unusual and innovative.

4. Recommendations for improving the ECOSENS methodology: summary of stakeholder feedback

In creating an energy source life cycle sustainability assessment, ECOSENS WP2 tried to **demonstrate process points at which a diversity of stakeholders could weigh in**, first within the framework of selecting and implementing an approach related to some already widely applied in the technocratic community, and then in trialing the instrument, and throughout in debating and critiquing its concept, application and outcomes.

However, were these opportunities adequate? Was the ECOSENS proposal the best methodological framework to demonstrate possibilities for stakeholder input? Was the trial implementation adequate? Was robust information drawn from the stakeholder judgments gathered during the WP2 test assessment (noting that this engaged a convenience sample of 40 experts from a handful of disciplinary or professional backgrounds[18])? And, the principal question formulated already at project proposal stage: how could the methodology be improved for future application?

To form at least a partial response, this section abstracts feedback and recommendations from three separate ECOSENS stakeholder events. As a reminder, WP2 engaged stakeholders at a workshop in March 2023 to give input to methodological development [MAYa]; in debate and reflection at the August 2023 Scientific Event [ZEL]; and after the online trial assessment exercise to examine selected outcomes with a critical eye during a March 2025 webinar. Some verbatim contributions and summaries from this last are included in Annexes 2 & 3.

Alongside the feedback from stakeholder events, this section also includes some internal recommendations from ECOSENS researchers.

It must be acknowledged that the recommendations gathered for improving the ECOSENS methodology are generally very high-level. We have expressed them in operational terms, but very often the recommendations would remain aspirational. Addressing broad-scale notions of societal decision making for sustainability, and implying both intensive and extensive efforts in data acquisition and participation, the stakeholder recommendations would require adjustments that surpass the context of the ECOSENS project or that are not directly applicable at the level of an LCA inventory/indicator approach.

Importantly, we have not verified the extent to which some of these recommendations are already effectively or fully implemented in the ECOSENS methodology, taking instead the opportunity to highlight the user demands on energy sustainability assessment at scale.

[18] A certain modest degree of diversity in discipline and professional role was accessed by the trial assessment sample. However, it remains emphatically a "convenience" sample, i.e. one that does not attempt representativeness but solicits willing participants who are easiest to access. A number of CSO stakeholders participating in the March 2025 webinar forcefully interpreted some trial findings as reflecting pro-nuclear attitudes, and recommended both more diverse sampling and the provision of more demographic information on future samples. Nonetheless, individual attitudes towards energy sources were not assessed by this poll and according to the first author's personal knowledge, among the 40 participants all would not identify as pro-nuclear. The suggestion is noted, however, that future exercises could potentially include pre-characterization of respondents' attitudes on several dimensions (energy attitudes, risk perception, etc.) using classical polling instruments.

4.1. International methodological workshop (March 2023)

ECOSENS organized two international workshops in March 2023. While these had different objectives, a largely overlapping set of stakeholders participated. Day 1 was organized by ECOSENS WP1, "A collaborative assessment of (imagined) energy worlds". The workshop on the "*Art and science of imagining energy futures*" [MES] enabled a both granular and high-level co-creative approach to revealing worldviews, values, and preferred pathways to a sustainable future. Day 2, the WP2 workshop entitled "*Decarbonizing Europe's energy system: Checking and choosing indicators for a sustainability assessment*," was organized back-to-back in the expectation that Day 1 could provide first insights with regard to "sustainability thinking," emphasizing how to embed sustainability assessment in a context of broader societal concern.

Day 2 turned to a more technical approach with the overall objective of validating and tuning the planned quantitative ECOSENS LCA. This can be considered to be a mid-level variety of stakeholder participation: selecting among proposed options to build an LCA tool, both methodological and substantive; debating and justifying those selections; and giving conceptual feedback on the future assessment approach.

[MAYa] provides full details of the WP2 workshop: profile of participants, preparatory and on-site materials, study questions, verbatim stakeholder input, and decision outcomes. The diverse group of experts/stakeholders debated methodologies and indicators for the sustainability assessment of energy production systems. They identified requirements for goals and scope of the assessment, considered proposed methodologies from the literature and validated the combination method proposed by ECOSENS, and reviewed the substantial list of 62 indicators and sub-indicators on three pillars. They also considered the difficult task of weighting indicators and at the end of the day directed that it should be performed by interdisciplinary experts in light of policy goals, after the calculation of bare assessment results.

At a higher conceptual level, participants identified critical issues for both the future ECOSENS life cycle assessment, and the overall pertinence and realism of such approaches for decarbonizing Europe. Definitions and practices of social sustainability emerged as key considerations, alongside the actual institutional will and ability to conduct sufficiently democratic decision making. **Participants revealed the risky narrow path between quantifying assumptions and "gaming" the numbers**[19], and underlined the need to perform iterative assessments to capture effects of earlier actions. They eloquently and patiently argued for whole-system approaches capable of taking into account cumulative risks and bioplanetary limits.

Within the rich feedback received during this methodological workshop, the following may be summarized as principal participant recommendations for a high-quality sustainability assessment. It must be noted that to implement these cogent recommendations in full would require data, human and time resources well beyond those of a limited project like ECOSENS.

[19] Finding emphasized in bold at the request of one reviewer.

PARTICIPATION FEATURES

- Leverage the combined strength of the interdisciplinary teams in participatory events. Tailor tasks to participant expertise whose potential may not be best used by "exact" rating tasks.
- Seek actively to include vulnerable populations among the stakeholders to ensure that social justice concerns are adequately reflected.
- A transdisciplinary collective decision approach could target not consensus, but rather a compromise that the assembled actors can live with.
    - A capsule process could convene a panel including different types of expertise, citizens, and representation of all those who should be at the table. Raw data can be collected and then analytic and decision-making processes should be combined to help the actors understand sustainability and learn to use the indicators and the data.
    - At a broad societal level, citizens and politicians need to be – and can be – educated to become more sophisticated in connecting assessment to phenomena in the real.

HIGH-LEVEL METHOD FEATURES

Selection of scope, construction of method

- Prefer more holistic, systemic and integrative assessments.
    - Ensure that the method can take into account cumulative stresses on ecosystem boundaries.
    - Account for the differing feasibility of various low carbon energy production methods.
- Verify that the method can take into account differing country-level realities as well as diverse stakeholder preferences.
- Measure technologies against their actual contribution to achieving decarbonization and eliminating fossil fuels, as well as against bioplanetary limits.
- Enable discussion and disagreement on high-level goals instead of building univalent assumptions into indicators.
    - "Economic growth" may be questioned as a societal goal.
    - Consider societal objectives such as accessibility and reliability of energy, abundant, sufficient and affordable for the consumer.

IMPLEMENTATION FEATURES

- Avoid weighting of indicators in early assessment stages because that may mask important issues.
    - Framing the regulatory and public policy decisions to come, settling the means to balance outcomes of both technical and social licensing, may be more crucial than the apportionment of indicator weights.
    - Thus, the ECOSENS LCA could be performed without weighting, then an interdisciplinary expert/stakeholder group could be convened to rank resulting decision options.
- Perform iterative assessments to capture effects of earlier actions (this requires integration of updated performance data).

- Use methods in sequence, moving from an integrative assessment that generates scenarios, to impact assessment exercises.
- Access “test beds” in university contexts to observe and improve participatory implementation.

INDICATOR FEATURES

- Fine-tune description of indicators in the socio-economic area to avoid ambiguity.
- Ensure that solid R&D, on which a relative consensus can form, is accessed and displayed in raters background information (fiches) on observed values of indicators.
- Consider the proposal for four areas of importance when selecting an energy mix and choose indicators in consequence:
    - Social sustainability: social progress – at global as well as at EU level; social feasibility (what kind of behavioral changes may be required); effect on social disposition (sociability); social exclusion; political stability and regulatory certainty.
    - Environment: CO_2 emissions; use of resources; other impacts; toxic waste emissions; compatibility with circular economy; respect of planetary limits; systemic approach to energy-water-food triangle.
    - Economics: Internal and external costs; investor risk.
    - Technological: Supply security; technology readiness level; technical feasibility (e.g. adaptability to climate change scenarios); resilience to unforeseen events both internal and external; vulnerability linked to degree of energy system distribution.
- Integrate objective social justice indicators so that protection of the vulnerable is not dependent on individual rater preferences.
- An indicator-based approach should tally both costs and benefits, and should distinguish between intrinsic benefits of an energy production technology and co-benefits of its application (such as increasing employment).
- Formulate indicators in terms of impact (rather than of emissions).
    - Enable accounting for differential impacts in distinct contexts.
    - Impacts should be appraised not in the absolute but taking account of their real interactions (additionality).
    - To facilitate societal interpretation and deliberation, expected individual-level impact of each indicator could furthermore be described in terms of loss or gain of life years or wellbeing.
- For certain indicators a hard threshold value of acceptability must be set by policy makers on the basis of empirical specialist findings and recommendations (e.g. in public health).
    - It must be possible to entirely eliminate from consideration a technology if it surpasses that limit, even if that technology appears to come out ahead of others on the long list of weighted indicators.
    - This “show-stopper” status does not, however, necessarily signify that the particular indicator is considered the overall most important to society.

INTERPRETATION and DECISION-MAKING PHASES

- Acknowledge factors beyond the technical and scientific observations translated in the indicators.

    - Importantly, public acceptance, politics and lobbies can determine the position of a country in the energy debate. For instance, political decisions show that nuclear energy was considered as “sustainable” in some countries, and “not sustainable” in other countries.
- “Scientists are capable of calculating anything, but the main issue is to produce a credible story for assessment by the public, and to convince the public authorities.”

Finally, a workshop participant experienced in supporting national decision makers offered a reflection that hearkens back to remarks by [WYN] and [WAD] that we earlier quoted (section 2.3), regarding a technocratic cultural view on the pre-eminence of quantitative data. This was followed by a pragmatic suggestion that goes beyond the specific context of a participative LCA:

> “The underlying assumption of assessment exercises tends to be that *if only we could find some better way to calculate our way into the best decision, then we could make better decisions*. However political decision making doesn’t work that way. In one context politicians said that scientific expertise and expert judgment are highly valued, but they don’t have time to read through the studies. What actually has an impact on decision making are **policy briefs** made by researchers including an expert recommendation. It could thus be helpful to **provide such a concrete empirical basis for political decisions, including a clear statement of how the experts derived their recommendation**.” [MAYa p21]

4.2. ECOSENS Scientific Event Stakeholder Panel (August 2023)

At the first ECOSENS Scientific Event (Dessel, August 2023), WP2 researchers presented the assessment approach and work achieved. A panel mixing former workshop participants, local stakeholders and other qualified critics took the stage to reflect on the sustainability assessment approach (before any trial assessment took place). The event concluded that "continued efforts to improve public participation and holistic assessment approaches are necessary for informed and democratic decision-making in energy policy." [ZEL p5] Distinct high-level recommendations may be summarized as follows; the material is derived from the event summary provided by [ZEL].

LEVEL OF ASSESSMENT AND CRITERIA

- Assess entire energy *scenarios* (combinations of technologies in a system) rather than compare single technologies in isolation.
    - Scenarios with nuclear need to be assessed against fully renewable or hybrid scenarios.
    - Scenarios should reflect policy projections on the actual proportions of different energy sources in the electricity mix.
    - Assessment can focus on actionable steps for implementing energy scenarios rather than debating exact target percentages for each technology by 2050.
- Methods should enable taking into account the complexities and interdependencies in energy, society, and ecosystems.
- To more usefully inform decision makers, assess a wide range of potential scenarios, including those with reduced energy consumption and alternative growth paradigms.
    - Prioritize resilience in scenario planning, presenting strategies that minimize resource use and dependency on sensitive or vulnerable technologies.
- Use IPCC guidelines, which evaluate energy technologies on multiple sustainable development criteria, beyond just emissions.
    - Enable consideration of the long-term impacts of energy choices on society, environment, and economy.
    - Broader sustainability criteria may include e.g. health, safety, and employment.
- Integrate assessment reflecting the principles of sustainable development, such as precautionary measures, distribution of costs and benefits, and ecological responsibility.

UNIQUE RISKS AND CHALLENGES OF NUCLEAR ENERGY

- Take into account the specific profile of nuclear risks including their extended time frame.
    - Nuclear territorial and intergenerational risks need long-term consideration beyond 2050, as nuclear projects can impact society for centuries.
    - Seek means to present for assessment the unique risks of nuclear energy (nuclear accidents, long-term waste disposal, geopolitical security, societal

trust issues, regulatory complexities) which are difficult to quantify and weigh against renewables in sustainability assessments.

POLITICAL DIMENSION OF SUSTAINABILITY ASSESSMENTS

- Recognize in construction and in interpretation that sustainability assessments cannot be neutral but are inherently political.
    - Choices about which energy sources to include, what criteria to prioritize, and how to interpret model results all reflect societal values and political agendas.
- Seek transparent, evidence-based, and democratic engagement with the full range of stakeholders or their proxy representatives.

PRACTICAL POLICY RECOMMENDATIONS AND REALISM IN IMPLEMENTATION

- Report clear, actionable policy recommendations.
- Inform realism by assessing which policy goals can be achieved within current technological and political constraints.

4.3. Internal reflection on the trial assessment (tool and analysis)

A life-size trial run of the methodology was performed in Spring 2024 in the shape of a detailed poll to assess four energy production methods on 62 (sub)indicators, relying on both raters' own knowledge and fiches. The fiches provided descriptive and quantitative sustainability performance data per technology, derived from available sources (including both published scientific literature and "grey" literature). This trial assessment did not seek representativeness of sample, but invited 20 energy/technologies professionals and 20 social science professionals to test-drive the online suite of questionnaires and fiches. Findings were reported and interpreted in [CONd].

Internal team reflections and debate yielded the following general proposals for improving the methodology in future runs:

CONSTRUCTION OF INDICATORS, QUESTIONNAIRE AND FICHES

- Consult stakeholders to validate description of indicators, especially social and economic indicators, to remove ambiguities (*see also Annex 1 described below*).
    - Consider adding more sub-indicators to capture nuances of performance or more dimensions of complex issues.
- Reflect with experienced questionnaire designers to formulate further simplified, consistent and unambiguous prompts.
- Update fiches to provide complete validated data on standardized and comparable rubrics, to ensure each fiche can be used in the same manner for the four technologies.
- Consider stakeholder suggestions for different types of data to be provided on fiches (impact rather than emissions, etc.)

SAMPLING

- Seek larger and more diverse populations of raters.
- Reflect with experienced polling professionals on the possibility of combining data from different populations who complete ratings on different reduced sets of indicators.

ANALYSIS OF ACQUIRED DATA (PARTICIPANT RATINGS)

- Collect information on whether respondents actually use fiches, and/or base their ratings on other expert knowledge, and/or value-laden opinion.
    - Assess the reliability of ratings as effectively representative of the data inventories or other sources.
- Reflect with experienced statisticians on the most appropriate analytic rules and tests to be applied given the form and quality of acquired data.
- State any hypotheses that would call for/justify the use of advanced statistics. Verify that sample size and characteristics support such statistical tests.
- In case of doubt prefer analysis and presentation remaining close to the primary meaning of data and informing transparently on variability.

INTERPRETATION AND REPORTING

- Report findings as results of polling, not as objective statements on the sustainability performances that were submitted to rating.
- Devote attention to the sources and meaning of variability observed in acquired data.

The deliverable report of findings was reviewed before submission by a member of the Advisory Board. Remarks on metrics are reproduced with permission in **Annex 1**. They show how the formulation of indicators for LCA could fruitfully be subject to stakeholder debate during the methodological development phase. The advisory input also cautions that political or governance differences between countries could be larger than sustainability performance differences seen among energy technologies, reducing the fitness of source-by-source ratings for decision making.

4.4. ECOSENS "Contentious indicators" stakeholder webinar (March 2025)

A set of 15-17 stakeholders including academic, NGO, and CSO representatives, who together represented a range of pro- and contra-attitudes with respect to nuclear power, responded to the invitation to attend an ECOSENS webinar in March 2025. Many of them had not participated in previous consultations. This event used results from the trial assessment, focusing on 8 (sub)indicators in particular. These results were selected because the standard deviation observed for ratings of nuclear sustainability performance on these 8 indicators displayed the largest dispersion of individual judgments, or dissensus, to be found among the 40 trial participants. Webinar discussion of what we proposed to label empirically as "contentious indicators" was designed as a workable opportunity to reflect on the content, method and process of the sustainability assessment.

CONCERNING THE INDICATORS

Guiding questions included: "if we judge that the dispersion or spread of ratings on these indicators means we are looking at differences of opinion or perspective, can we gain insight into these differences? Can you recommend supporting indicator information that could improve the assessment's access to multiple perspectives?"

Acknowledging one participant's challenge to the fitness of taking *"the place of other actors to try to justify why they decided that the tomato is red*", the stakeholders nonetheless applied themselves thoughtfully to offer numerous technical remarks (**Annex 2**) on how the 8 indicators might be differentially interpreted. These could be taken into account for the refinement of (sub)indicators and/or their description. Overall, participants highlighted the need to access meaning:

- If indicators or criteria appear (through acquired rating results or through stakeholder deliberation "in a group setting") to be meaningless or ambiguous, adjustment is needed.
    - Engage stakeholders during methodological development to debate and refine indicators, identifying ambiguities, pertinence, etc.
    - Refine the written description of indicators (fiches). Ensure that raters have a good understanding of exactly what is proposed to assessment.

- "Simplifying each indicator by drawing its boundaries quite strictly is one very technical approach that could have its value."
- Remove indicators that are too complex, produce too much variability in response, or appear without pertinence (e.g. without application to all four technologies). This will enhance the credibility of the instrument[20].
- Consider the use of (complementary) methods other than polling to access richer representations of stakeholder values, perceptions, preferences and political positions that are more meaningful for decision making.
- Organize further deliberation of findings obtained on ambiguous indicators to pinpoint the variability factors that are important for policy making.

CONCERNING THE OVERALL APPROACH OF LCA AS PRACTICED

As for the webinar request for "recommendations to improve the assessment methodology," very numerous concerns and reasoned critiques were heard. These are presented in **Annex 3** under the following headings:

- LEVEL OF COMPARISON AFFORDED BY ASSESSMENT METHODOLOGY: Single-technology assessment approach; "comparison" of sources in a synergistic system; incommensurability and ensuring comparability; functional unit; lifetime.
- FEATURES OF THE ASSESSMENT TOOL AND APPROACH: Assessment approach (questionnaire); reference data (fiches); indicator ambiguity; indicator pertinence; missing indicators.
- IMPLEMENTATION: Assessors' use of rating scale; information regarding volume of "NO ANSWER"; sample bias.
- FINDINGS: Perceived "random" distribution of responses; divergence from international literature.
- REALISM OF ASSESSMENT OUTCOMES AND OF INTERPRETATION
- DECISION-MAKING UTILITY OF ASSESSMENT

Below is a summary list of actionable recommendations to improve the ECOSENS sustainability assessment, selected by the first author from the webinar.

METHOD AND APPROACH

- Develop and justify choice of participatory approach with reference to works in social science and humanities.
- Assess diverse energy mix scenarios, rather than comparing technologies one-to-one.
- Scenarios should take into account e.g. the proportions of technologies in a projected energy mix, and the synergistic effects of varying proportions upon sustainability.
- Background data fiches: Consider the use of normalizing factors, guidance when data ranges are provided, and explanatory tables expressed in a uniform functional unit to help grasp performance by technologies largely differing in scale, lifetime, etc.

[20] Nonetheless, as proposed by one stakeholder, certain imperfect indicators could act as "canaries in the coalmine" revealing bias, confusion, inattention or other response quality issues (such as when the average finding could be seen as highly divergent from international literature; or when uniform middling scores are attributed on "proliferation of sensitive materials" to technologies that do not include such materials).

TECHNOLOGIES AND INDICATORS

- Remove instances of technologies that present very different profiles and affect the overall reference numbers (example residential solar).
- Improve the factual input (indicator descriptions and fiches) so that people who have little technical background can read it and form their view.

PARTICIPATORY IMPLEMENTATION

- Enlarge and diversify sample, including energy specialists and generalists with a previously demonstrated range of views or attitudes (with respect e.g. to nuclear power).
- Conduct assessment in a guided environment with a facilitator present to explain the reference data and intended scope behind the indicators, and the rating scale.
- Ensure that stakeholders can take the time to gather and consider reference information and to complete the assessment comfortably, including by remunerating the time spent.

One stakeholder affirmed that for a polling approach to LCA, “simple questions only must be posed to experts who qualify in education and experience. They must sign their opinions and be accountable for the correctness of answers.”

INTERPRETATION AND REPORTING

- Enhance transparency by providing (demographic) information about respondents (while respecting anonymity if that was offered at the time of presenting the survey).
- Where largely divergent ratings are obtained, test relationships to respondent characteristics (who is saying what?)
- Acknowledge different standpoints, perspectives and judgments when these are revealed by variability in ratings.
- Check and weigh interpretations against field experience (example: “maturity of waste management practices” has different meanings in the nuclear or the RES field which should not be obscured).

SPECIFIC FUTURE RESEARCH

- Look at what the 8 contentious indicators have in common.
- Bring forward the analysis of differences between respondents and their grouped replies.
- Consider the propensity of individuals to proceed by comparison, and investigate how this can be leveraged or made compatible with highly complex scenario assessment.

5. Final discussion and conclusions

> "If you have 30, 40, 1000s of respondents, and proper statistics for each, you can derive different information from each grouping. However, even if it's only 5 people, if they cannot come to a consensus enabling decision, it's still a problem to be solved. So the question arises of 'What do you want to do?'" – *Stakeholder participant, ECOSENS webinar 3/25.*

5.1. What is wanted for an improved sustainability assessment?

Myriad recommendations to improve the ECOSENS sustainability assessment were presented in Section 4 above. The ECOSENS team recognizes, with thanks, the high volunteer engagement in complex tasks by all the stakeholder participants, and their thoughtful intra-group cooperation during the feedback events.

Some of the stakeholder recommendations appear directly actionable to finetune our existing LCA inventory/indicator approach to comparing the lifecycle sustainability performance of technologies 1:1. At the final ECOSENS meeting, the project coordination characterized the methodology as "imperfect but perfectible,"[21] and the conference presentation by the WP2 leader, main author of the methodology, summarized learning over the course of the project in this way:

> "The paper highlights the potential of participatory approaches to produce input for technically grounded decision-making, while also discussing **key challenges**, including the complexity of the assessment framework especially the **judgement of the entire lifecycle, the interdependence of energy mix components, and the substantial effort required from participants.**
>
> "The results, based on the averaged individual responses (for environmental, economic, and social pillars), suggest that respondents perceived no major differences among the evaluated technologies, with none approaching the maximum score. **Future applications of the methodology should focus on capturing more subtle distinctions,** while recognizing that all technologies are viewed as valuable for the energy transition, with their differences influenced by technological advancements and market dynamics within specific contexts." [CONe; emphasis added]

The outlook for new applications and further work to "perfect" the approach by the WP2 leader after the close of the ECOSENS project (Oct. 2025) includes:

- Possible integration of methodology in the IAEA - INPRO framework (discussed in that working group in 2025, after presentations in 2024)[22].
- Open access to methodology via ECOSENS website: uploading of questionnaires, fiches, and guidance.

[21] D. Diaconu, overview presented at the final ECOSENS Conference and Project General Assembly, Milano, September 2025.

[22] As well, the four scenarios (and nine sub-scenarios) "for climate neutral sector based on nuclear new technologies and variable renewables" [CONb] developed in ECOSENS but not assessed by the LCA approach, could be tested in energy modelling through IAEA and NEA.

- Elaboration of the methodology in new projects.

This outlook offers clear opportunities to *assess for feasibility, prioritize and apply* actionable recommendations from among those collected during the ECOSENS lifetime. Indeed, it would be appropriate and feasible to continue to associate a range of stakeholders, including civil society representatives, in such work.

The weight of stakeholder feedback, however, suggests an answer to the question of "*What do you want to do?*" that extends **beyond the finetuning of the indicator-based polling instrument and fiches**. Our stakeholder informants indeed expressed a vision for a societal approach to sustainability assessment, and sustainability decision making, that integrates a high level of complexity, transparently reflects a diversity of values and preferences as well as market and political realities, gives voice to vulnerable and empowered members of society, cogently and iteratively captures the synergies of elements loaded into energy mix scenarios, and seeks to enable decision making cognizant of both planetary boundaries and moral imperatives.

Within that vision, life cycle sustainability analysis would form a single, limited tool. It could be complemented by the use of calculators such as EUCalc/TPE [MWA] to rapidly deliver performance numbers for integrated energy mix scenarios, enabling a combined quantitative-qualitative elaboration of decision data.

Moreover, the LCA approach would need to be complemented by more in-depth qualitative consultations that make the most of the different rationales and knowledge brought to bear by individual raters, and enable too a collective level of thought and consolidation. Stakeholder feedback gathered elsewhere in the project (concerning WP3) appears relevant in this connection: "*CSO stakeholders highlighted (…) their commitment to evidence-based contributions and not theoretical thoughts. They emphasised their role as issue-focused contributors whose expertise stems from their empiric work in specific domains of public interest, including but not limited to environmental protection and social justice considerations"* [MIH].

Overall, the sustainability assessment approach claimed by our participants would require a range of tools to build up an **analytic-deliberative** process [NAS] that is **fair and competent** [REN]. This is an ideal that has been sought across a good part of the period of TA development that we reviewed in the first part of this deliverable. In this perspective, we include in **Annex 4** some resources to identify participatory technology assessment (pTA) techniques that have attempted to combine competent analysis and fair deliberation to inform societal policy decisions.

5.2. An informal evaluation

Returning to that first framing we gave to this deliverable, we contextualized the work of ECOSENS with regard to the historical objectives of technology assessment as a social decision tool. We found that ECOSENS WP2 played out some of the classical tensions that persist in the search to "make participation become real" in the realm of TA.

[DIX], at a symposium that also hosted the author of the "ladder" of public participation [ARN] Sherry Arnstein, asked in the very early days of TA: *"Why is it that citizens are not asked to specify the world they want and the alternatives which they desire?"* Of note, ECOSENS did

ask that of stakeholder participants, in the very first International Workshop "The art and science of imagining energy futures" [MES] held back-to-back with the WP2 workshop "Decarbonizing Europe's energy system: Checking and choosing indicators for a sustainability assessment" [MAYa]. The two workshop reports present a multidimensional, multistakeholder view, rich and sophisticated, of desires for a sustainable society respectful of planetary limits, and for fair and competent assessment.

In our TA literature review for this deliverable, we furthermore sought examples of life cycle sustainability assessment that had successfully engaged diversified stakeholders – and found almost none. Builders of a calculator to test low-carbon transformation pathways at European and member state scale consulted future users (public policy actors and CSO representatives). [MWA] The resulting EUCalc tool and approach[23] are indeed of great interest and could conceivably be employed in a multistakeholder exercise approaching the ideal envisioned by ECOSENS stakeholders. By contrast, however, [UNECE] and [JRC] LCAs, which greatly surpassed the scale of ECOSENS by mobilizing multiple authors and myriad models and technical references, stopped short of integrating stakeholder consultation or participation beyond governmental circles.

Acknowledging all the differences in scale, resources and remit, it appears important to state for the record that **ECOSENS innovated by creating an LCA approach that can engage and be informed by stakeholders at various process points**, from upstream methodological development to assessment to analysis and interpretation. This was no mean feat, and a worthy outcome for this Coordination Support Action (CSA), whose formula according to the European Commission funders is to bring together existing knowledge and advance it through stakeholder engagement in order to support future research and development.[24]

WP2's three consultation events provided ample pertinent stakeholder feedback on the strengths and weaknesses of the approach. This feedback is accessible through [MAYa], [ZEL], and the transcript-based annexes to the present deliverable. The stakeholders' critical input stands as a review of the work, viewed differentially as successful or failed according to the issues and values prioritized by each participant.

In their guidelines for the evaluation of representative deliberative processes, the Public Governance directorate of the OECD [PUB] single out three dimensions that must be evaluated in sequence: process design integrity, the experience of the participants, and pathways to impact. While the ECOSENS LCA is presently not designed as a deliberative process, these dimensions have been partially approached in the stakeholder review reported in this deliverable. Future elaborations of the ECOSENS methodology should foresee systematic evaluation on the criteria set out by [PUB].

[23] https://www.european-calculator.eu/

[24] "Coordination and Support Actions (CSA) stand apart from [other European research instruments] by focusing on measures that facilitate cooperation, policy harmonization, capacity building, and the dissemination or exploitation of results. Instead of funding direct research or innovation activities, CSAs support work that coordinates existing initiatives, strengthens networks, or assists stakeholders in making better use of existing knowledge and research outcomes.

"CSAs often center on activities such as networking, workshops, policy dialogues, stakeholder engagement, standardization efforts, training, and outreach. The emphasis is on improving research and innovation ecosystems, aligning diverse projects, or supporting the development of shared strategies among stakeholders. They may also help shape future research agendas or policy frameworks." Source: https://myhorizongrant.com/understanding-the-differences-between-ria-ia-and-csa-projects-in-horizon-europe/

An informal auto-evaluation of the attempt to create a participative LCA can be conducted with reference to [PORa], who in 1977 proposed a reduced set of simple questions to approach typical "formative and summative" evaluation of a TA exercise. Table I below offers the first author's subjective rating of ECOSENS WP2's sustainability assessment exercise on these criteria.

Evaluative issue	First author's subjective assessment of ECOSENS WP2 work/publications, informed by stakeholder feedback	(Reader's own assessment…)
Pertaining to TA validity:		
Are the best available data used?	+/++	
Are analyses conducted according to accepted principles?	++	
Are inferences sound and supported?	+/++	
Do projections conform with actual developments? On what time frame?	(cannot be assessed at this time)	
Pertaining to utility:		
Is the TA study readable and understandable?	+++	
Is the study credible to various potential users?	+	
Is the study influential on user attitudes and behaviors? Does it affect decision making?	(cannot be assessed at this time)	
Over what time period is the study found to retain its usefulness? Is it quickly out of date?	(cannot be assessed at this time)	
Pertaining to advancement of the methodological state of the art:		
Does the study document its techniques sufficiently to be of methodological use?	+++	
Does it provide a useful case application of certain techniques?	+++	
Does it represent a novel application? With implications for further extensions?	+++	
Does it introduce new techniques?	++	

Table I: Informal self-assessment on [PORa] criteria for evaluating TA exercises

ECOSENS WP2 perhaps succeeded mainly in the innovative creation of a "perfectible" tool, coherent with the European Green Deal ambition of having citizens as the driving force of the transition. The opportunities for stakeholder input to WP2 took a first step toward empowerment as framed by the [EEA]: "not only to shape top-down initiatives and proposals but also to express disagreement and propose alternatives." The consulted stakeholders' myriad remarks and recommendations provide a deep well from which to draw means for "perfecting" the ECOSENS sustainability assessment. **Annex 5** presents the reflections by the WP2 leader upon reviewing this sum of material in this deliverable, and highlights the recommendations viewed as most operational for improvement of the methodology in the near term.

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Annex 1 - Advisory Board Member feedback on [CONd]

As member of the ECOSENS Advisory Board, Markku Lehtonen of (University Pompeu Fabra Barcelona) agreed to review the report of trial assessment results [CONd] before publication. Formal remarks were generally taken into account in the final version of the report uploaded to the project portal and website. Below are Lehtonen's brief fundamental reflections on methodology and metrics.

In the deliverable author's opinion, these reflections demonstrate how the detailed formulation of indicators for LCA could fruitfully be subject to stakeholder debate and refinement during the methodological development phase. Moreover, these comments can be interpreted to suggest that ECOSENS WP2 took a desirable path by soliciting early stakeholder input on the high-level goals of assessment, and could continue on such a path by collecting detailed input on desired scope, time scale, etc.

Carbon emissions

The comparison of greenhouse gas/carbon emissions is a good illustration of some of the limitations of LCA (of course, any method has its limitations). While it is theoretically and formally certainly correct to note that the life-cycle carbon footprint of nuclear is small – of the same order as that of renewables – in practice, the extent of the actual life-cycle carbon emissions from different energy options depends on many other factors that an LCA study cannot capture. Perhaps most clear example is the importance of the timescale, the estimated urgency of climate mitigation, and the "opportunity costs" between different energy technology/system options. For instance, if building X amount of nuclear generation capacity takes 10-15 years, whereas the same amount of renewables could be built in 3-5 years, the LCA comparison between different technologies loses some of its relevance. Likewise, energy technologies differ in terms of the effort in terms of money, capital (including political capital), workforce, cost of labour, training, etc. required to build X amount of generation capacity, which in turn influences the society's ability to reduce carbon emissions.

Proliferation of sensitive materials

The metric used for the assessment of this criterion – "effectivity of non-proliferation measures" – seems somewhat biased, or at least highly surprising. Given the serious risks involved in the possible proliferation of nuclear/radioactive material, it seems fully logical that the nuclear sector would have developed far more advanced methods for non-proliferation than the other energy sources. These latter obviously pose their own security and geopolitical risks, as the report rightly notes, but these are not commensurate with nuclear proliferation risks. Hence, this is somewhat of an "apples vs. pears" comparison, and rather misleading as such. Summing up, the question addressed – the nature and implementation of non-proliferation measures – is of course relevant for energy policies yet the title should be something else than "proliferation of sensitive materials". Maybe this could be classified as a governance indicator, named as the "governance/institutions of non-proliferation", or something similar.

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

This indicator is of course fully legitimate and relevant as such. It belongs to the same category of "governance indicators", and presents partly similar problems as the indicator "proliferation of sensitive materials". The fact that nuclear scores high on this indicator is partly a reflection of the long history of nuclear power, but also and above all of the nature of waste generated. Radioactive waste generates quite different and arguably far greater dangers and "challenges" than the more conventional types of waste from the other energy sources. My intention is neither to belittle the importance of managing those more ordinary types of waste nor to deny the fact that even renewables produce significant amounts of highly problematic and long-lived waste. However, arguably radiation risks are in a different category than most if not all other types of waste, and this is why comparing these qualitatively different waste problems on an equal footing is problematic. This indicator is of course closely interlinked and should hence be analysed in conjunction with the others in the same section, in particular, "Impact of generated wastes (S_i 1.8.2) Radioactive wastes (generated)" and "Impact of generated wastes (S_i 1.8.4) Long-term effect of deposited wastes".

A final remark, on governance: is this an energy-source-specific or a country-specific issue?

On the whole, I'm not 100% convinced of the adopted approach, which associates the maturity and quality of governance measures with specific technologies. The approach is not completely devoid of logic, given that energy industries are in many ways global in nature, and have developed international guidelines and even their unique governance structures – with nuclear energy and nuclear waste as prime examples. However, countries vary widely in terms of their governance capabilities, and cross-country variation is probably in many cases far greater than the variation between energy technologies.

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Annex 2 -Technical remarks on indicators: potential sources of rating variability (from 3/25 webinar)

Fifteen to 17 academic, NGO or CSO stakeholders participated in an ECOSENS webinar on 12 March 2025 entitled “Checking contentious indicators” and bearing on selected indicators from the findings of the trial LCA [CONd]. The 8 indicators chosen for reflection were those on which ratings of nuclear technology sustainability performance showed the largest dispersion from the mean (in this case, those displaying a standard deviation of >2.5 points on the 5-point scale).

This annex organizes and summarizes a selection of technical remarks that could aid in **understanding the variability of ratings on these indicators**. The remarks could support the refinement of these sustainability performance indicators for future trials of the ECOSENS assessment methodology. Verbatim or summary remarks by different individuals are separated into distinct paragraphs. They were not necessarily uttered in this order.

Principal subjects of discussion during the webinar included:

- *Pertinence* of indicators on which a large dispersion of ratings is seen.
- *Uncertainties* inherent to the selected indicators and the difficulties arising then in pinpointing the reference information to be provided in fiches.
- Apparent *ambiguities* in formulation of indicators which could trigger different perceptions or areas of focus in different raters.

A reply could be made to the latter point: the indicators are indeed explained (disambiguated) in the reference fiches. Nonetheless, the fact that outcome ratings were not uniform demonstrates that the raters did not make their assessment on a uniform basis. Faced with the same reference data, they gave different interpretations (at least on the 8 indicators selected for discussion). Moreover, it is not possible to say whether raters in fact consulted the fiches during their participation in the assessment exercise. In any case, they apparently did not limit themselves to the data represented there to formulate their judgment.

Importantly, the webinar participants were explicitly reminded not to “perform the assessment” (provide individual judgments on relative sustainability performance). They were asked instead to reflect on potential sources of variability in the acquired ratings, due to e.g. features of the indicator, psychological or cultural dispositions of raters, or sundry other real-world conditions.

It may be noted that participants very often constructed their argumentation using *comparison of technologies* on a given indicator. This approach contrasts with the original trial assessment instruction (which did not directly concern the webinar participants): *rate each technology on each indicator with regard to its own performance, not in comparison with other technologies*. This contrast between spontaneous discursive behavior and LCA instruction is important to notice because the observed recourse to comparison may indicate a typical or comfortable cognitive procedure. If comparison was so readily used during group discussions, it may possibly be used – implicitly or explicitly – by individual raters during the polling task. This propensity and potential should be investigated for future applications of the ECOSENS methodology, and adjustments found if necessary.

The observations collected below (among very many others) suggest the need for more in-depth qualitative consultations that make the most of the different rationales brought to bear by individual raters. Among other proposals, a sequenced process could first unveil different perspectives on components of energy technologies for the green transition, identify indicators that could capture these perspectives, interpret their importance to decisions about sustainability, and finally negotiate how they should be taken into account and what further research is needed to clarify remaining points.

(Sub) Indicator	
1.6.2	Emissions (other than C) - Ozone depletion potential
1.9.2	Impact of accidental situations - Impact of severe accidents (considering mitigation/prevention…)
2.3.1	Cost - Cost of the investment (capital cost)
2.3.3	Cost - Cost of decommissioning (including environmental remediation)
2.6	Levelized Cost of Energy (LCOE)
3.11	Dependency on government support (funding/ incentives, such as tax credits or subsidies)
3.12.1	Risks - Level of risk reflected in insurance needs
3.12.2	Risks - Proliferation of sensitive materials

***Table II**: The 8 (sub)indicators discussed in the "Contentious Indicators" webinar. Pillars as defined by [CONc,d] are represented by color: Environment (green), Economics (pink), Social (blue).*

During the webinar, the selected indicators shown in Table 3 were presented by pillar for discussion in parallel subgroups. Each subgroup had access to a summary description of each indicator drawn from [CONd], reflecting information that had been provided to trial assessors.

OZONE DEPLETION POTENTIAL

Ozone layer depletion is about 6 chemicals I believe; the question is to what extent are they used in the production of the life cycle of these technologies?

How important is this? What is the weight of the indicator as a whole? In simplistic terms, the ozone hole is "a problem solved" and has been already for a long time.

Ozone depletion is not a very important factor in the overall picture for these technologies. If we were to assess the power network, the concern could arise if it's a question of the old network in which outdated technologies are used for transformers.

Depending on how far back you go in the life cycle, whether you fully consider uranium mining, you may have different opinions on potential production of the harmful chemicals.

IMPACT OF SEVERE ACCIDENTS (CONSIDERING MITIGATION/ PREVENTION)

The combination of prevention versus mitigation makes it more complex to actually respond to this indicator.

Some may have responded based on the actual impact of a severe accident when it happens, whereas others may have responded taking into account how well prepared the nuclear industry is against the occurrence of accidents: due to the high volume of safety regulations you might have people rating it as highly sustainable on that point.

People in nuclear might say, "'yeah we do a lot on prevention, safety culture, passive safety". But once something happens, the consequences can be serious.

Some may focus on prevention and even elimination through passive safety, while others would focus on the complexity of mitigating the accident.

Objectively, consequences could be very different according to whether the advective cloud goes over the sea or over a city.

For some people without specialized knowledge, mitigation may be very uncertain: is it even possible to mitigate the effects of a severe accident? It may not occur to them that agriculture could still be possible in an affected area. And you could say that we are still busy mitigating Chernobyl and Fukushima.

Nuclear accidents are described as very low probability but with serious consequences. Some raters might focus on the low probability, while other of course focus on the grave consequences.

"Risk" entails chance x impact - and much of the prevention is concentrating on chance whereas impacts are lost out of sight. The assessment should be of risks, including both chances (preventive measures) and impacts (how many people, how much environment, how much economy is impacted). And how about uncertainties... especially in assessment of chances.

If you put nuclear accidents into perspective with renewable energy sources the scale is quite different. If a blade comes down off a wind turbine perhaps someone will be hurt but not all Europe has to stay inside their house, has to take measurements, has to take an iodine pill or things like that.

There is a question of interpretation of "severe accident" against "accident" or "incident". Persons familiar with the presence of numerous incidents might rate the technology as highly sustainable whereas others may consider worst-case scenarios.

Some may remember only the worst accidents or most severe consequences.

Nuclear accidents like Chernobyl or Fukushima may remain more persistent in our collective memory. Or possibly the younger generation coming up that did not get exposed to all the news will have a different attitude. They may have different expectations for nuclear with the notion that innovative technologies like fusion are the future.

Nuclear energy has a strong association with risk. If you talk about vehicles, the risk of motor accidents is not the first thing that comes up. Risk perception is a very prominent factor in evaluating nuclear technology as opposed to other energy sources.

Other technologies, like hydro or gas are much better understood by the majority of people. They can imagine it. Whereas nuclear power may seem very safe but on the other hand, not many people know what it is about. This could explain the dispersion of opinions.

COST OF THE INVESTMENT - CAPITAL COST

Why would lower capital costs mean higher sustainability? The fact that there can be a high capital cost can have very different reasons. The most visible reason is always emerging technology: technology that's new, that has a very high capital cost, but can be extremely sustainable. We see that, for instance, with the intermittent, more variable renewable energy sources. In the '90s and the 2000s, those were extremely expensive. Nowadays, they're very cheap.

Lower capital costs (more favourable investment conditions) = higher sustainability performance? This is rubbish. This is different from project to project. FOAK (First of a kind) can be very high, NOAK (N^{th} of a kind) can be very low (examples: solar, wind, small hydro, small decentralised sustainable biomass)… In NOAK, the N can be unrealistically high before capital cost becomes a competitive issue (see the case of nuclear - especially SMRs).

The lack of clarity on the cost of financing can perhaps explain the high SD. When you consider the cost of investment, it would be interesting to have also a perspective on R&D and market trends to see whether new technologies tend to get cheaper or more expensive.

I understand the capital cost has its value depending upon the application. Say, for example, where if the current country or a system has high input cost on running an existing power generation system or the lack of energy resources like coal or something, for them transitioning into something new is worth the capital cost. So it is subjective.

It's dependent on the current situation of the country and how energy production is aligned. Say for example the country has limited non-renewable resources like coal, or the population growth is significant, then they need to look for an alternative. The capital investment itself is required, whether it would be sustainable or not, because they need to adapt to the growth. The sustainability part only comes in at a bigger picture level.

- *The more people, the more energy needed: you need to invest in the construction of the machine, within national limits.*
- *Conversely as you witness depletion of the population, maybe it's not a priority to invest in more machines.*

There are some external factors, whether it is political or the labor force or the market itself influencing those decisions. So even the capital cost itself could be like the projected cost is something, but execution cost is going to be significantly different.

If we just look at nuclear, for instance, today, we see that there are really problems with investment, with capital costs. Things like a Hinkley Point C, go double the budget, triple the foreseen periods.

You know the starting estimate (or the "overnight" cost) but not the final cost, as interest rates change, there are delays, etc. There are many uncertainties in financing costs.

Optimism vs. pessimism plays its part.

In Europe, where I believe there've been dozens of schemes of subsidies in parallel, it's impossible to calculate what is the cost and what have been the subsidies. You need thousands of figures like this to have an investment. This is such an extremely complex issue that it needs week-long seminars and not 20 minutes of discussion.

Costs have a synergistic importance for sustainability. Why? Well, look at nuclear now, we see in the Netherlands at this moment that there is less investment in renewables because there is a lot of investment going to nuclear, which isn't delivering. But the fact that the renewables aren't delivering either at the moment, because there's no investment in it, has already its effect on sustainability.

It you wanted to make a favorable case for nuclear you could calculate the financing costs according to the entire 80-year life cycle of the plant, against a renewables project that might last 20 years.

Why there is so much uncertainty regarding capital cost attached to nuclear is because nuclear plants are highly cost intensive, so more capital invested at the same time in CAPEX, I mean capital expenditure. So, it's a specific way of structuring the capital that is taking quite a long time. And also in terms of insurance of the capital, you have to rely on the state. That creates uncertainties of making sure that the capital is not to too costly at the end. And so that's why there are so many de-risking tools for the capital attached to NPPs.

I think that we are having quite an interesting discussion. And it's going beyond the exercise. But for me to hear it all depends on how the risk is split and shared and how it's structured and that demands a quite specific observation on how it's exactly made and who bears it at the end. And that depends on the national situations and also on the continents and the companies and the plants in itself.

To ease the work of future assessors, the fiche should contain: the clarity of cost of financing, who's taking the risk, who bears the burden, the lifetime considered and also maybe the evolution of the nuclear market trends in terms of technology development and so on.

COST OF DECOMMISSIONING (INCLUDING ENVIRONMENTAL REMEDIATION)

Cost of decommissioning should also include waste management and circularity.

It's difficult to look at the long term in decommissioning because the cost will be in the future. Another element to be considered is the number of cases; we have rich information about the costs of investment, but less data on decommissioning and environmental remediation, infrequent and unfamiliar.

We don't know what period to consider for waste management because some waste will be there forever.

It's difficult for a rater to understand what will happen in 20, 40 or 60 years and what the costs will be.

The process and decisions on waste disposal are different in each country. So many things are controversial and depend on national policies.

Public information or discussion in the media may influence the people considering this question.

LEVELIZED COST OF ENERGY (LCOE)

LCOE - plant lifetime is a problematic issue, because the predicted plant lifetimes are currently rather a political than an economic issue. But still LCOE is a useful tool.

Lifetime is quite different in the case of nuclear, windmills or gas.

In the literature, nuclear comes out as having the highest LCOE, with one exception: OECD NEA[25]. That means there can be bias according to which source the fiche relies on.

Which costs are taken into account to conclude that renewable energy sources have a higher cost than nuclear? How does this take into account the differences between an individual placing a panel on an individual roof and connecting its production to the network, vs. large solar or windfields?

– Extra service costs must be taken into account, such as the purchase of batteries for individuals to remain independent of the grid.

– ECOSENS researcher reply: If you are a prosumer adding electricity to the grid you contribute to some costs, e.g. the services for constant frequency, for constant voltage, and maintaining the balance between consumption and production. It is very complex in the case of solar, and if you consider the entire cost it is not as cheap as it may appear.

Additional remark by Advisory Board reviewer: "LCOE has its limitations, and is probably most useful for individual firms to help them make investment decisions. LCOE does not fully account for the 'system costs', and therefore can actually discriminate against nuclear. But the whole issue of system costs is complex, and the outcomes depend on assumptions concerning the potential and deployability of different technologies, for instance."

DEPENDENCY ON GOVERNMENT SUPPORT (FUNDING/INCENTIVES, SUCH AS TAX CREDITS OR SUBSIDIES)

Dependency can vary across countries and it's not necessarily obvious how the financing is structured.

The key factor behind dependencies on government support are subjective political decisions by the politicians.

One argument made by the nuclear promoters is that the renewable, renewable targets, policy targets defined in terms of what percentage of renewables you have to have in your grid counts as a subsidy, an indirect subsidy to renewables. So that's an argument. And then another issue is of course the historical perspective. There's always an argument for infant industries, that you have to support them

[25] This stakeholder assessment of the LCOE literature has not been verified for the purposes of this deliverable.

at the start but then they will survive on their own after a while. But you could argue that hasn't happened in the case of nuclear after seven decades.

There is a huge, huge difference between the direct subsidies, then there are indirect subsidies, then there are so-called gross subsidies and moreover what was the most common for nuclear are the so-called hidden subsidies. Like the fact that we don't collect and we don't really know whether we need the money for the nuclear backend, you know.

The issue of subsidies of government support is still too much of a black box, making it complex to actually evaluate how many subsidies each energy technology gets.

The money they put into studying nuclear safety and all the other expenses that they don't need to do for windmills for example, we don't know about this. It's almost never explained.

These financial discussions about nuclear are discussed a lot more in the media than for water or gas. The more something is in the media, the more interpretations are possible.

I think there's too many uncertainties still, to really make this a meaningful criterion.

A fact check can clear out these questions, but then it comes down to interpretation: what is "support"?

There's probably a huge variation between respondents as to what they count as support: ownership, credit?

Differences in what is considered "private" or "public sector" according to country could guide different interpretations of this question. Would a state-owned company be seen as "supported" by the state?

Regulation, market regulation, safety regulation, are all issues that could count as government dependency. In that sense, these energy sources are not at all independent of the states. So for me, it's almost an irrelevant question. Or not irrelevant: dependency is very central, but it should probably be formulated in a different manner.

Then there is the question of preference: do we want the state to intervene? Do we integrate into the assessment what people think about the kind of society we want to live in, how the world is changing, how willing people are to accept state intervention? For Europeans it comes back to national security and the crazy things that are happening on geopolitical level.

Dependency, from my perspective as a social scientist, can be almost synonymous of support. The public could say "dependency is a bad thing" for sustainability, but it can also be "a good thing" because the support is there. Then there is the opinion each person has regarding how much we as individuals should contribute with our taxes to the system to then have electricity, energy for all.

RISKS - LEVEL OF RISK REFLECTED IN INSURANCE NEEDS

Insurance - this indicator only works when realistic insurance coverage is used. The fact that nuclear liabilities are capped and government-covered distorts the picture because it excludes a large part of liability from the scope.

Nobody wants to calculate, for instance, what the cost of a nuclear accident would mean.

There's two ways of capping nuclear liability insurance. One is the amount of liability that is basically covered by the operator. And that can go from very little, like 80 million euros in Bulgaria, to unlimited in Germany. But what is more important is the part for which you need to have insurance. And that is in Germany, two and a half billion. You need to keep that in perspective. The first year in the aftermath of Fukushima needed about 85 billion euros of cash flow. Thus the two and a half billion for which in Germany would be maximally insured is of course only a drop of water on a hot plate. But the problem is that the nuclear insurance market is heavily regulated and therefore it is very difficult to compare that with other technologies where you don't have this kind of regulation. And if you would really let the nuclear sector insure itself as it should, it could, but power prices would go up a few percent.

RISKS – PROLIFERATION OF SENSITIVE MATERIALS

U-233 and U-235, as well as H3 (tritium) are also proliferation material (beyond those detailed in the indicator description provided during the webinar)

This is not only about materials, but also about technologies (e.g. spread of reprocessing technology (chemistry) and enrichment technology).

If they are gonna build more and more small modular reactors, and put them everywhere, then you have also, a type of proliferation of more, more, more.

Yes, I am worried about the use of uranium 238 in weapons; but that concern fades away in comparison with my fear that weapon materials may proliferate with the use of SMRs including the associated delivery of reprocessing technology. Those two components should be split up.

Many stakeholder comments questioned the relevance of "proliferation of sensitive materials" to the assessment of renewables, hydro and natural gas, and wondered how such ratings could be made or interpreted. Calls were heard to remove the indicator to reduce the potential for confusion and to enhance credibility.

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Annex 3 - Concerns and recommendations on assessment methodology (from 3/25 webinar)

Here we present methodological concerns raised by the stakeholder participants in the webinar described in Annex 2. This rich material corresponds to a serious endeavor of joint reflection – so rich that it remains thickly textured even when reduced and organized by the first author under rubrics. We may consider that the content corresponds to a true work of deliberation, for which we thank those volunteers.

Of the great mass of concerns and related reflections recorded in the three hours of group work, some give rise to specific recommendations for improving the ECOSENS sustainability assessment approach. Those found most outstanding or actionable by the first author are drawn out and summarized in Section 4.4 above.

The text in italics below is drawn from the webinar plenary and subgroup transcripts[26]. Verbatim or summary remarks are presented in distinct paragraphs. This organization represents either the logical progression in one person's thoughts, or, inputs by separate persons. The paragraphs were not necessarily uttered in this order.

Of note, similarly to the set of indicator comments gathered in Annex 2, we observe here many concerns related to comparability of energy sources. Participants grapple too with the need for a systemic analysis of a synergetic dynamic, arguing for a scenario-level comparison rather than a technology-level approach.

LEVEL OF COMPARISON AFFORDED BY ASSESSMENT METHODOLOGY

SINGLE-TECHNOLOGY ASSESSMENT APPROACH

One-to-one comparison of technologies is a reductionist tool (cutting up a problem into smaller problems, addressing them, putting all together) that does not reflect the real-world reality (which is highly interconnected!).

"COMPARISON" OF SOURCES IN A SYNERGISTIC SYSTEM

Don't compare technologies 1 to 1, but compare scenarios with different energy mixes. The methodology is not technologically neutral. Variable renewable energy sources (RES), for instance, will be the backbone of the energy system in 2050 with a very large majority of power coming from those sources. This weighs most criteria different for variable renewables than the other technologies. The individual "performances" per technology are not decisive – and show synergetic effects on sustainability of different mixes. These performances can therefore only be a small part in a total sustainability assessment. It is misleading to take them in a static, comparative perspective.

A 1:1 comparison is not fruitful because objectively, selected sources will be represented in unequal parts in energy mix. The contradiction between objectively unequal weighting and the "neutral" or standardized weight of sources evaluated without reference to real proportion may make it difficult for people to reply to the questions.

Moreover a high performance on a sustainability indicator may be trivial for outcomes when the source is playing a very small role in the energy mix.

[26] We furthermore gratefully acknowledge reception from one NGO participant of a two-page set of notes and numbered recommendations, which we have taken the liberty of quoting, or abstracting alongside similar transcripted remarks from the same or other stakeholder participants.

The alternative is energy scenarios which you compare together. You look in deep at how the various criteria will play a role. In a mix with so much % of this technology, and so much % of another technology, in 2050, you ask "is this least costly? Is this most effective in CO2 reduction, in nature protection?" Then you will get the complete picture. But you must look at the mix: If you only look at nuclear, it will not be the 100% source of energy that will be responsible to 100% for performances on the various criteria.

There are input factors as well: technologies become favourable or unfavourable in specific scenarios depending on the performance data entered into the model. The data must be based on solid information, from validated sources: this is a sine qua non.

INCOMMENSURABILITY AND ENSURING COMPARABILITY

For some indicators the impacts of different technologies are incommensurable.

- *An accident associated with RES cannot be compared with a nuclear accident in terms of gravity and scale of consequences: a wind turbine blade may fall and injure someone but there will be no need for large populations to shelter in place, take iodine pills, etc.*
- *Scale intervenes at other levels, too: the spatial footprint of different technologies, the costs and impacts of collective or individual installations (example: a regional nuclear plant vs. solar panels on a single family's roof).*

It facilitates comparison if indicators can be expressed for all the energy sources on a common monetary basis. However, it's not easy to bring different scales, impacts, lifetime, etc. to a single basis, and there is disagreement on the cost of intangibles.

Which normalizing factors can we use to conduct fair comparisons rather than looking at isolated specifics?

Overall outcomes will be affected by the weights given to each indicator as well as the normalizing factor.

It could be easier to cross-check and find an even basis for comparison by using a table that lays out what is considered an incident, an acceptable accident, a severe accident for each energy source, and assigning financial cost or human cost to each category. Such a table would nonetheless be difficult to produce.

FUNCTIONAL UNIT

Importance of expression through a unique or systematically applied functional unit.

[UNECE] used common denominator of "delivery of one kWh to electricity grid".

It would be very useful to have a table comparing for instance the cost to build a nuclear plant of a certain type and a hydroelectric plant, expressed in megawatt output.

LIFETIME

The expected lifetime of each installation also has to be taken into account.

- *Of note, different generations or types of nuclear reactors have different lifetimes. Is it correct to give a composite sustainability score?*
- *The Time Zero at which you initiate the assessment will have an impact: do we take into account the achieved years for an old plant while simultaneously rating an entirely new technology or installation?*

FEATURES OF THE ASSESSMENT TOOL AND APPROACH

ASSESSMENT APPROACH (QUESTIONNAIRE)

This is not really an assessment but a poll.

The assessment here is qualitative, based on expert judgements and reduced to a poll of ranks attributed on a set of criteria. Either the approach should be resolutely on the side of a poll, with attention to revealing biases in a well-characterised sample of respondents, or, it should engage an expert panel to go into the detail of reasoning and present diverse elaborated views on the object of assessment.

The method should be more grounded in disciplines of estimations and assessments.

The participatory aspect of the assessment methodology should be grounded in appropriate social science/humanities references.

REFERENCE DATA (FICHES)

The fiches should be based on transparent scientific data, not on grey literature based on "WNA consultation" as main source for nuclear, as is the case with the UNECE (2021) report.

The factual input needs to be readable and understandable to persons with less technical background.

For indicators such as "Potential for Ozone Depletion", the fiche provides a very large range for nuclear (covering the worst case scenario in uranium mining). There is no guideline to help raters place the cursor.

INDICATOR AMBIGUITY

"Potential for proliferation of sensitive materials": because it's meaningless for three technologies, there could be misunderstanding of the indicator as perhaps assessing other things, such as impact on the environment by different threats of the technologies.

Indicators need to be defined or reformulated to make sure that raters have a good understanding of what is proposed to assessment. (See many examples in Annex 2)

Some indicators are too complex to understand which component is driving assessment judgment.

Simplifying each indicator by drawing its boundaries quite strictly is one very technical approach that could have its value.

- *That means that the number of indicators would increase substantially and that always makes it more difficult to interpret results.*
- *Nonetheless it could be useful to break down the indicators in order to discuss specific issues in a group setting.*

INDICATOR PERTINENCE

We should really get this indicator "proliferation of sensitive materials" out, because it's meaningless and it's going to confuse people or generate critiques.

Capital cost: Sustainability sometimes comes at a cost, for instance, a very foolproof system to prevent accidents is costly. So lower capital cost is not necessarily an indicator of desirability. Such an indicator may not be foremost in sustainability assessment. It could be background information to support the decision maker.

The indicators should be policy-relevant, and that may imply value-laden decisions which are taken differently by different stakeholders. For instance, regarding the indicator "Dependency on government support", the question is not simply the sustainability of a monetary figure, but one of vision. "Do we want the state to intervene? How willing are citizens to accept state intervention in the energy sector?

What does intervention imply in related areas, like national sovereignty and security, which are volatile questions in today's geopolitical context?"

"Level of risk properly reflected in insurance" only works when you examine realistic insurance coverage. Capped insurance in the nuclear sector distorts the picture, because it keeps a large part of liability out of the scope. This difficult point is exacerbated in the discussion on SMRs because there are calls to reduce the caps even more for smaller reactors, resulting in an even more distorted picture.

The level of impact of different indicator components or areas must be taken into account and prioritized.

Ozone depletion does not appear to be an important part of the overall sustainability picture of these four energy technologies – especially considering that we are not assessing sub technologies for which it may be pertinent (generators; networks).

MISSING INDICATORS

Waste management costs would need to be included in the assessment of decommissioning.

IMPLEMENTATION

ASSESSORS' USE OF RATING SCALE

We do not have access to the rationale used by each rater to assign a sustainability level (from 0-5) to each technology for each indicator.

In some cases this individual factor appears to be significant: how to explain that RES are rated as less sustainable on average than nuclear technology for the indicator "Decommissioning (including cost of environmental remediation"?

Are raters referring to future expectations or to past experience?

INFORMATION REGARDING VOLUME OF "NO ANSWER"

We learn that "no answer" amounted to approximately 10% of replies. Should this be integrated in statistics or graphs?

*Is that volume due to fatigue? Raters had to provide 62*4 judgments (over several weeks).*

SAMPLE BIAS

Provide more transparent information on the composition of the sample (expertise, background, demography, etc.)

It would be interesting to learn which assessors are generating the spread represented in the standard deviations under discussion: are the technical experts disagreeing, or the other stakeholders? Is the "contentious" character of the indicator due to experts or others?

The base of 20 or 40 expert inputs on a very wide spectrum of issues will not yield statistically significant information – certainly not when there is a bias in expertise (towards nuclear).

Don't only ask input from people with a strong pro-nuclear bias, but also with backgrounds in other energy fields, including generalists with overview.

*Contrary to what was said, it makes sense to keep a proliferation indicator [*identified by the group as meaningless for 3 of 4 rated technologies*] in order to reveal honestly that the respondents misused anonymity and presented their political agenda [*by attributing comparable, middling proliferation performance scores to all 4 technologies*]. This brings important empirical evidence: if we want to have objective research on topics like this, then simple questions only must be posed to experts who qualify in education and experience. They must sign their opinions and be accountable for the correctness of answers. Ideally the respondents should be asked how they frame proliferation in the 3 non-nuclear options, and did they engage scientific data in their assessment.*

FINDINGS

PERCEIVED "RANDOM" DISTRIBUTION OF RESPONSES

The perceived "random" distribution of ratings on some indicators could be explained by various factors, according to webinar participants:

- *Due to insufficient input data, guessing. (example: Ozone depletion potential)*
- *Due to irrelevancy, guessing. (example: Ozone depletion potential)*
- *In both cases, due to people respecting the instruction to reduce their proportion of "NO ANSWER".*
- *Due to small sample size.*

DIVERGENCE FROM INTERNATIONAL LITERATURE

If the rating result is diverging strongly from international literature, this should function as a red flag.

REALISM, SENSITIVITY OF ASSESSMENT OUTCOMES AND OF INTERPRETATION

Compare the interpretation of nuclear power scores reflecting "a robust approach in managing generated wastes", and then intermittent renewables score lowest reflecting "less mature waste management practices". In my daily practice we still struggle with what are we going to do with high level waste and we're struggling with that already for 70 years. And if you look at RES I think, "come on, hold on, these are 15 years on the market and they're now already working on recycling industry of wind blades". It oozes bias. The report needs to be credible. And if we then try to look at it on a meta level, what we see is that people have different opinions on certain issues. That needs to be reflected.

DECISION-MAKING UTILITY OF ASSESSMENT

If you have 30, 40, 1000s of respondents, and proper statistics for each, you can derive different information from each grouping. However, even if it's only 5 people, if they cannot come to a consensus enabling decision, it's still a problem to be solved.

DIVERSE DIRECT RECOMMENDATIONS ON ASSESSMENT METHODOLOGY

- Conduct assessment in a guided environment with a facilitator present to explain the reference data and intended scope behind the indicators, and the rating scale.
- Remove instances of technologies that present very different profiles and affect the overall reference numbers (example residential solar).
- Ensure that stakeholders can take the time to gather and consider reference information and to complete the assessment comfortably, including by remunerating the time spent.
- The factual input needs to be improved here so that people who have not much background can read it and then say "Okay, I think that, A or B"; that would help, that would help a lot.

SPECIFIC FUTURE RESEARCH

- Look at what the 8 contentious indicators have in common.
- Bring forward the analysis of differences between respondents and their grouped replies.

Annex 4 - Resources for the selection of pTA techniques

Researchers and practitioners have devoted some amount of work to creating inventories of participatory methods that can be applied in the broad context of technology assessment or energy-related policy development. These "pTA" (participatory TA) methods are generally less targeted and formalistic than LCA, and often focus on qualitative data collection to inform decision. The intention of providing this material here is therefore not to substitute such techniques for LCA. This annex is intended rather to give access to some historic and still useful references, in particular the European project COWAM 2 (Communities and Waste Management) in which several ECOSENS partners participated, and the Engage2020 project which developed an online tool to select techniques. The reports and techniques generally target a **rich collection and restitution of (often qualitative) stakeholder input**, which corresponds to some expectations expressed by stakeholders at the ECOSENS events.

Of note, the various sources do not largely converge on which methods may be considered most appropriate, but apply different criteria and filters. This suggests that it is indeed useful to consider several references or compilations in developing a particular participative technology assessment initiative.

COWAM 2 WP1

WP1 of the COWAM 2 Euratom project that ran 2004-2006 aimed at capacity building among local and regional stakeholders in radioactive waste governance. It tested how participatory technology assessment (pTA) methods can "offer a consensual framework and a platform for deliberative co-decision among scientific and societal actors at the local level." [LAE p3]

> "Appropriate techniques may be provided by (…) participatory technology assessment (pTA). Technology assessment is a 'scientific, interactive and communicative process which aims to contribute to the formation of public and political opinion on societal aspects of science and technology' [citation]. The attribute 'participatory' emphasises the active involvement of societal stakeholders as discussants and assessors. The present study (…) provide(s) an up-front overview for local stakeholders willing to participate in radioactive waste governance." [FLU p1]

[FLU] found that most pTA methods had been adapted from general social research methodology or group moderation/workshop techniques, with just a few explicitly developed in the context of participatory approaches. The report offered advice on matching method with the frame (or context, setting) within which involvement takes place, with an emphasis on maximizing legitimacy, influence and utility. Criteria for identifying methods were provided along with potential indicators or questions. Selected methods were briefly presented:

- Consensus Conference
- Future Search Conference
- Cooperative Discourse
- Area Development Negotiation
- Citizen Jury
- Citizen Advisory Group
- Multi-criteria Mapping.

This review of selected pTA techniques delivered conclusions under the following headings:

"Framing is more important than the technique chosen; Representation of different (social) groups is crucial; Output is more than decision taking (e.g., information techniques provide to decision makers, the legitimacy they add to policy outcomes, and the positive effect they have on civil society and the development of a more informed and civil democratic culture. A good match of technique and context is necessary; combination of different techniques and more intense methods is preferred; process matters and demands active formation (especially good communication, government commitment; flexibility and responsiveness of the lead agency)." [FLU pp10-11]

[LAE] refined these criteria by providing a "lens" for selection of pTA method in light of social learning goals and topical realm. These were respectively operationalized and detailed under the following rubrics:

Social Learning Goals:

- Possibility to justify positions
- Contributing innovative ideas/creative solutions
- Empowerment
- Access to scientific expertise.

Topic:

- Perceived level of complexity
- Existence of prior general knowledge
- Degree of uncertainty (variability, measurement errors, indeterminacy, lack of knowledge and ignorance) – as opposed to ambiguity (variability of legitimate interpretations according to values or (legal) norms)
- Level of controversy.

Engage2020

Engage2020, an FP-7 project (2015-17) of the European Commission, aimed to "mainstream" public engagement in responsible research and innovation under the upcoming Horizon 2020 programme. It was coordinated by the Danish Board of Technology Foundation, well known as the 1987 originators of the "Consensus Conference" technique: "a type of meeting that makes it possible to include the public and their experiences in the technology assessment."[27] Engage2020 created an interactive online "action catalogue" enabling filtered selection of techniques and their description.

For the purpose of this ECOSENS deliverable we set various filters, reviewed descriptions, and iteratively selected a dozen techniques that appear particularly suitable for pTA from among the 57 found in the catalogue. The below links lead in each case to a page giving access to short and long presentations of the technique, checklists to describe its application, and critical assessment of strengths and weaknesses.

https://actioncatalogue.eu/method/7395 Citizens Hearing

https://actioncatalogue.eu/method/7403 Citizen Summit

https://actioncatalogue.eu/method/7412 Citizen Visions on Science, Technology and Innovation (CIVISTI)

[27] https://www.co-intelligence.org/P-ConsensusConference1.html

https://actioncatalogue.eu/method/7413	Consensus Conference
https://actioncatalogue.eu/method/7386	Deliberative Mapping
https://actioncatalogue.eu/method/7388	Deliberative (Mini-publics) Workshops*
https://actioncatalogue.eu/method/7398	Deliberative Polling
https://actioncatalogue.eu/method/7399	Delphi Method
https://actioncatalogue.eu/method/7418	Perspective Workshop
https://actioncatalogue.eu/method/7426	Participatory Modelling
https://actioncatalogue.eu/method/7436	Q-Methodology
https://actioncatalogue.eu/method/7437	Reflexive Interactive Design

Annex 5: WP2 leader's reflections on lessons learned from the deliverable and highlighted recommendations

The analysis makes a significant contribution to understanding how stakeholder feedback can be integrated into the development of a complex sustainability assessment methodology. Overall, the work offers a **balanced and well-argued perspective on the value of these contributions**, as well as on the practical limitations encountered in applying and refining the methodological instruments.

One of the strongest elements of the work is the way it highlights the consistent involvement of stakeholders and the relevance of their observations in strengthening a more robust methodology. The diversity of viewpoints and comments demonstrate real engagement and a high level of maturity in addressing sustainability issues. The recommendations received were not only recorded, some of them were effectively incorporated into adjustments to the ECOSENS methodology; a particularly significant example is the decision to remove weighting in the initial phase of the LCA assessment. This shift allowed weighting to become an exploratory exercise in assessing methodological sensitivity, thereby enhancing transparency and relevance.

The work also acknowledges that not all recommendations can be implemented directly. Many require additional resources, specific expertise, or conditions that exceed the scope of a project such as ECOSENS. Moreover, some suggestions are influenced by participants' familiarity with energy technologies or by their underlying preferences, giving these recommendations more strategic than immediate operational value. This differentiation is presented in a mature and realistic manner, demonstrating a clear understanding of the process's objective limitations.

A major contribution of the document is the section "**Participatory technology assessment: An old question, persistent tensions",** which provides valuable contextualization of the methodological approach. It underscores the historical tensions in participatory technology assessment, and also the traditionally limited role of stakeholders in such evaluations. Through well-chosen examples, the deliverable establishes the conceptual foundation necessary to understand why ECOSENS proposes an innovative and ambitious approach aimed at addressing long-standing methodological challenges.

Project results confirm both the potential of participatory methods to deliver valuable input for technical decision-making and the complexity of undertaking such an approach. The 2024 test of the methodology—evaluating four technologies using 62 indicators and sub-indicators—demonstrated the usefulness of the conceptual framework as well as its challenges. Although representativeness was not the objective, the involvement of 20 technical experts and 20 social science experts provided a solid basis for validating the online instruments and data sheets. The results indicated that evaluators did not perceive major differences between technologies, highlighting the need for methodological refinement to better capture subtle distinctions.

Based on this experience, the ECOSENS team acknowledged the received suggestions addressing indicator construction, questionnaire and fiche design, sampling, data analysis,

and reporting practices. These suggestions are valuable and include clarifying social and economic indicators, adding sub-indicators, simplifying question phrasing, updating fiches for comparability, expanding sample diversity, and consulting statisticians to establish sound analytical rules. The work also stresses the importance of transparent reporting of data variability.

The Advisory Board's observations complement the analysis, emphasizing the need for deeper stakeholder involvement in methodological development and cautioning that governance differences between countries may outweigh differences between technologies, thus limiting the usefulness of ratings for policy decisions.

A key conclusion is that **stakeholders conceive sustainability assessment far more broadly than as a technical refinement of LCA**. They envision a societal approach capable of managing high complexity, reflecting diverse values and preferences, including vulnerable groups, and capturing system-level synergies within energy scenarios. In this vision, **LCA becomes only one tool within a broader analytical-deliberative process supported by rapid quantitative tools and in-depth qualitative consultations.**

From a pragmatic standpoint, the methodology developed and tested has proven its value in facilitating comparative discussions about technologies relevant to the energy transition, particularly through strong stakeholder engagement in evaluation and decision-support. However, **its effective future application depends on a well-developed national or European framework, appropriate resource allocation, and adequate training**. In this broader evolution, incorporating the recommendations presented in this deliverable represents only the first step.

Finally, it is useful to mention some lessons learnt at the level of W2 coordination:

1. **Investing time and effort in participation for technoscience decisions**

- Stakeholders engage more when their values, interests, and expertise are recognized and integrated into the decision-making process.
- They are more likely to participate if they believe their input will genuinely influence decisions and if the organization demonstrates responsiveness to their concerns.

2. **Compensating insufficient expertise and supporting meaningful participation**

- Prepare: Provide preparatory workshops, learning modules, or tailored briefing materials for non-experts. These should explain key technical concepts, outline uncertainties, and present multiple viewpoints in accessible formats.
- Tools: Use simulations, visualizations, and scenario-planning tools to communicate complex information intuitively, enabling informed dialogue without requiring deep technical knowledge.
- Co-design: Involve stakeholders in shaping the participation process itself. When they help define goals, framing, and questions, their engagement becomes deeper and more focused, especially in areas where their insights add the most value.

3. **Allocating suitable resources**

- Iterative design: Allow time for piloting, feedback cycles, and multiple rounds of engagement.
- Financial resources: Budget appropriately for tools, outreach, and stakeholder compensation.
- Stakeholder coordinators: Assign dedicated staff to manage communication, outreach, and logistical aspects of participation.
- Background materials: Provide briefings or toolkits tailored to varying levels of stakeholder expertise.
- Deliberative formats: Go beyond surveys by organizing citizens' assemblies, stakeholder panels, or participatory technology assessment forums.

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