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Exploring sustainability, societal perception, licensing and non-electric applications of new nuclear technologies: perspectives and achievements of ECOSENS, HARMONISE and SANE projects

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Abstract. Small Modular Reactors (SMRs) and Advanced Modular Reactors (AMRs) are seen today as promising solutions for enhancing Europe's energy supply security and contributing to global climate change mitigation. Their successful deployment, however, is contingent upon robust political support, widespread public acceptance, and the establishment of a harmonised safety regulatory framework. Furthermore, demonstrating their potential for non-electrical applications is crucial for stimulating broader interest and accelerating their development. Within the framework of the EURATOM Research and Development programme, these multifaceted challenges are concurrently addressed through the ECOSENS, HARMONISE, and SANE projects, whose results contribute to advancing knowledge pertaining to the societal, licensing, and safety challenges inherent in emerging nuclear energy technologies, with the aim to expedite their implementation within the European Union. The paper presents the up-to-date public perception on current and emerging nuclear technologies in the context of major societal challenges and details the outcomes of a comprehensive sustainability assessment of nuclear energy across its entire life cycle, employing a methodology co-developed by a diversity of stakeholders, including regulatory authorities, industry, academia, and civil society. Additionally, the paper introduces a novel economic model based on the System of Provision approach, designed to inform and assist decision-makers in formulating effective nuclear policies. These results provide a comprehensive perspective on nuclear energy, considering not only technical and economic aspects but also the broader societal and environmental implications. In addition, the paper provides recommendations for the harmonisation and standardisation of methodologies, codes and standards developed on the basis of the analysis of regulatory requirements for light water reactor technology. Finally, it outlines expectations arising from investigations into the safety aspects of non-electrical applications of nuclear energy, particularly focusing on residential heating, industrial processes, and other off-grid uses such as hydrogen production.

1 Introduction

The contemporary global landscape is profoundly shaped by pressing environmental and geopolitical imperatives. Specifically, the discernible effects of climate change, manifested through phenomena such as prolonged heatwaves, severe droughts, extensive wildfires, and increasingly frequent extreme weather events including floods and tornadoes, now constitute daily realities for European Union (EU) citizens. Concurrently, the imperative of energy security, significantly accentuated by geopolitical aggressions, has underlined the vulnerability of existing energy supply chains in Europe [1]. Addressing the ambitious target of net-zero emissions by 2050 necessitates a concerted effort from all responsible stakeholders, encompassing policymakers, industry, research institutions, academia, civil society, and the general public, across all economic sectors [2].

In this critical context, both current and innovative nuclear energy technologies, particularly Small Modular

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Reactors (SMRs) and Advanced Modular Reactors (AMRs), are increasingly recognized as promising means to support comprehensive decarbonization of power generation and enhance overall energy system resilience, bringing increased safety and sustainability attributes [3]. A growing number of SMR designs are currently under active development and exploration. Should their inherent promises of flexibility, reduced footprint, and passive safety features be fully realized, they could significantly complement the fluctuating nature of renewable energy supplies, thereby contributing to a more diversified and robust energy mix [4].

Recognizing the substantial potential of SMRs to contribute to both energy security and climate change mitigation goals, the European Industrial Alliance for SMRs has proactively put forth a strategic agenda. This agenda proposes specific actions aimed at "*facilitating and accelerating the development, demonstration, and deployment of the first SMR projects in Europe in the early 2030s*" [5]. This initiative underscores a collective commitment at the EU level to expedite the commercialization and integration of these novel technologies.

However, the timely and successful implementation of SMRs extends beyond merely resolving technical and safety issues. It critically depends on the presence of robust political support for a national nuclear program, which must be underpinned by a holistic analysis of nuclear energy's sustainability across the entire life cycle of nuclear investment. This analysis must intricately integrate economic and financial considerations tailored to the specific national context, ensuring long-term viability and attractiveness.

Furthermore, the successful realization of nuclear projects necessitates a favorable societal perception and broad public acceptance. Understanding existing public sentiments and concerns is paramount, and the transparent involvement of all stakeholders in the decision-making process, from the earliest stages of project conceptualization, is essential to foster trust and ensure legitimacy [6].

Emerging innovative nuclear technologies also demand a comprehensive review and adaptation of existing regulatory requirements. These frameworks, often stemming primarily from established light water reactor technology, require harmonisation and standardization at the EU level concerning methodologies, codes, and standards. Concurrently, the assessment of innovative nuclear reactor components must be streamlined to facilitate a more efficient and consistent authorization process across the EU Member States, thereby reducing regulatory burden and accelerating deployment [7].

Beyond traditional electricity generation, SMRs offer considerable potential for diverse non-electrical applications, including the production of process heat for industrial applications, district heating, and hydrogen production [8]. This expansive potential requires further in-depth investigation, with a particular emphasis on thoroughly understanding and addressing the specific safety aspects associated with these non-electric uses.

Recognizing the interconnectedness and complexity of these challenges, the Horizon Europe Euratom programme has strategically addressed them through three distinct but synergistic projects: ECOSENS, HARMONISE, and SANE. These projects share a common overarching objective: to systematically improve knowledge concerning the societal, licensing, and safety challenges inherent in both existing and emerging nuclear energy technologies. Through their collaborative research and documented findings, they aim to provide robust, evidence-based support to EU and national decision-makers, the broader nuclear community, and the general public, thereby contributing to informed policy development and enhanced understanding.

Using a deliberative approach, ECOSENS – Economic and Societal Considerations for the Future of Nuclear Energy in Society [9] investigates citizens' views and risk perceptions, benefits and potentials of current and new nuclear technologies in the context of major societal challenges. Nuclear and socio-economic scientists and societal stakeholders (authorities, industry, academia and civil society) are engaged to explore and co-construct possible energy futures and the role of nuclear energy therein. Sustainability assessment of nuclear energy technologies over the entire life of the nuclear investment including the nuclear fuel cycle was explored based on a new methodology developed by integrating multiple perspectives. A novel economic model based on the system of provision approach, was developed and tested within the project to provide a path to more holistic and sustainable approaches to nuclear energy, considering not only the technical and economic aspects, but also the wider societal and environmental implications.

The current regulatory requirements dedicated to protecting people and the environment from the harmful consequences of ionising radiation have been primarily formulated considering Light Water Reactors. Emerging innovative fission (e.g. SMRs and Generation IV reactors) and fusion technologies (e.g. ITER test facility, DEMO reactor) require reconsidering and potentially reformulating these requirements. This topic is addressed within the HARMONISE project [10] (`https://harmonise-project.eu/`) which has put forward a comprehensive approach for studying the body of knowledge needed to accomplish harmonization and standardization of methodologies, codes and standards as well as the assessment of nuclear reactor components. The project considers such issues as the gap analysis in the existing requirements for licensing of innovative nuclear reactors as well as the fusion power plants, possibilities to achieve the technology-neutral, risk-informed and performance-based approach regulations.

Non-electric uses were identified in EU SMR pre-Partnership as one of the high-level R&D needs, and the understanding of the potential applications and their limitations as well as the challenges in integration of nuclear energy to end use were seen as important issues to be studied. Non-electric uses will be an important way to diversify the income streams of nuclear plants, as electricity production will become increasingly competitive. Nuclear has unique advantages in non-electric uses as it can produce lot of energy locally for large local uses. Safety Assessment of Non-Electric uses of nuclear energy – SANE project investigates the potential of non-electric usage of nuclear energy (such as residential heating, industrial processes, hydrogen production), the safety aspects of reactors designed for non-electric use, as well as the safety implications of the end use. As many of the applications are novel, their use needs to be properly communicated to various stakeholders, and for this the project includes work on risk communication.

2 Societal perspective on current and emerging nuclear technologies

Nuclear research, technology deployment and decision-making need to better align with societal values, needs and concerns by engaging the public and ensuring that a plurality of stakeholders and disciplines can weigh in on sustainability assessments. A first step in assessing the public attitudes towards the use and development of nuclear energy technologies, including new and emerging technologies, was a systematic literature review of relevant social science research on social determinants of attitudes towards nuclear energy and ethical considerations, in the context of climate change, energy security, and sustainability [11]. Following the PRISMA protocol, the analysis comprised 82 articles published since 2011, indexed in scientific databases and showed that public support for nuclear energy is generally negatively associated with climate change concerns and positively associated with concerns for energy security. Moreover, the higher the perceived benefits of nuclear energy for energy security and, to a lesser extent, for the mitigation of climate change, the more open or (sometimes reluctantly) favorable attitudes towards nuclear energy are. However, differences between countries have also been observed, and it has turned out that the topic of SMRs, despite rising in importance, is understudied in terms of social research.

The subsequent empirical research focused on public views, concerns, and expectations surrounding the SMRs and involved qualitative and quantitative methods. Firstly, comparative case studies have been conducted in six European countries to examine qualitatively public perceptions and views on SMR technology and its potential role in future energy policies. In this stage, based on joint research protocols, we combined conducting desk research (gathering country-specific information on the inclusion of SMRs in energy strategies and the concomitant public debate), focus group discussions in Spain, the Czech Republic, Belgium, and Slovenia (with the general public, residents near nuclear power plants, and regional stakeholders) and consultations and interviews in Slovakia, Slovenia, and the UK. Secondly, we designed and conducted in the summer of 2024 representative public opinion surveys of the adult population in three countries: the Czech Republic (n = 1022), Spain (n = 1001), and Belgium (n = 1200). Encompassing a large set of questions, these comparative surveys, too, centered around views on SMRs and nuclear energy by the public, especially in the context of climate change and energy security challenges.

The research and key findings are described in [11]. The desk research revealed that the policy strategies of the Czech Republic, Slovenia, Belgium, and the UK foresee deploying SMRs in the future and act accordingly, while some Spanish companies take the technology rather as an opportunity to engage in R&D&I, and Slovakia's stance is less obvious based on open-source data. Among the countries considering SMR deployment, there is evidence that the number of web news articles related to SMRs has increased substantially since 2021, suggesting an intensification of the public debate. However, as Figure 1 shows, the awareness of SMRs was limited in the surveyed populations.

The qualitative data indicates that the public lacks information about SMR technology and perceives the promises of its future deployment as potentially hopeful but vague and uncertain. Mixed views prevail regarding the comparisons with traditional large power plants or renewable energy sources, with research participants mentioning opposing pros and cons. The benefits of SMRs for tackling climate change are often unrecognized or deemed too hypothetical to cope with the pressing climate crisis issues. The energy security benefits of SMRs are understood but acknowledged less than the energy security benefits of large traditional reactors. Possible barriers to SMR technology implementation include local opposition to SMR projects, nuclear waste management and disposal concerns, safety concerns (more reactor sites require more oversight and imply more risks), qualified workforce deficiencies, or legislation and licensing challenges. Some participants preferred experts, not politicians, to decide about SMR development, and considered the room for possible public involvement in decision-making to be unclear. Lastly, concerns about the transparency of an SMR technology introduction have been raised, especially in Slovakia and Slovenia.

Two international workshops *"The art and science of imagining energy futures"* [12] and *"2050 Here & Now Scenario Workshop"* engaging a large range of societal stakeholders explored their perspectives on sustainability and energy governance assessments (and the role of nuclear energy therein) and tried constructing together with technical experts' possible energy futures, taking into account ongoing energy transitions and climate change and other major societal challenges.

3 Nuclear energy sustainability

To assess the nuclear energy sustainability, a new methodology was developed applying a set of principles and evaluation criteria to some existing methodologies in a joint effort engaging experts in energy and stakeholders representing the civil society, academia, industry. Its basic principles, selection criteria, evaluation areas and indicators have been agreed upon during two international workshops, integrating the plurality of views. The new methodology co-created in ECOSENS combines through a social lens three existing methodologies: NESA [13] and KIND [14] of IAEA and LCA/LCIA-JRC [15], into a new one, which assesses Environmental life cycle, Economic life cycle and Social life cycle, based on 3 High Level Objectives: Contribution to planetary wellbeing, Reliability and

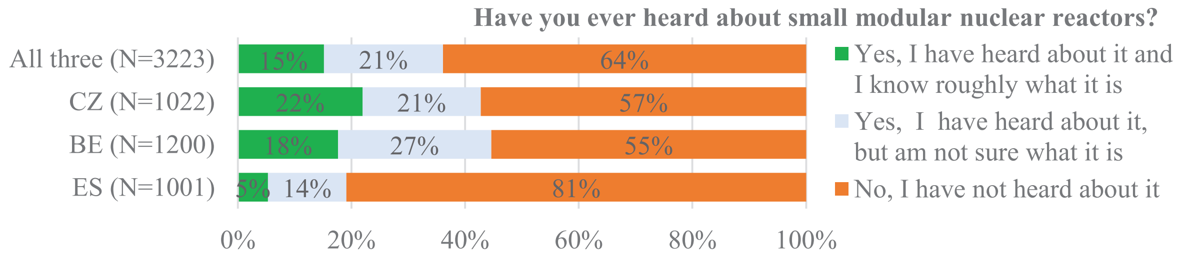

Fig. 1. Awareness of SMR technology among the public (Data source: 2024 public opinion surveys in Belgium, Spain, and Czechia) [11].

resilience of supply, and Social feasibility, and 62 indicators [16] (Tab. 1).

The analysis of nuclear energy sustainability elaborated based on this methodology allowed for a better understanding of nuclear energy characteristics in terms of sustainability, a clearer view on the total costs of the entire life cycle and an assessment of its contribution to a climate-neutral EU energy system by 2050 [17].

Recruiting participants for this assessment required a balanced, diverse group, ultimately divided into two key sub-groups. Sub-group 1 consisted of 20 socio-humanistic experts from ECOSENS partner organizations, contributing insights into social, ethical, and policy aspects of energy systems. Sub-group 2, included 20 participants with strong technical expertise, providing valuable perspectives on operational and technological issues in the energy transition. The assessment, conducted in spring 2024, involved exclusively higher-educated individuals, 45% of whom held a PhD. The sample was nearly evenly divided by specialization (50% technical, 50% socio-humanistic) and gender (55% female, 45% male). Most participants (64%) were aged 36–50, with 17% aged 18–35 and 19% over 50.

A reflexive polling methodology was used to evaluate the sustainability performance of selected technologies. Respondents individually rated each indicator and sub-indicator, guided by structured online fiches containing explanatory notes and performance summaries based on public sources. This approach combined expert judgment with standardized information, enabling a transparent, informed, and context-sensitive assessment across technical, environmental, and socio-economic dimensions.

Responses were recorded on a 1–5 scale (1 = minimum performance, 5 = maximum performance). Results were collected for all 62 indicators and sub-indicators. Figure 2 illustrates the data representation for the Carbon Emission indicator.

The contributions of all indicators are aggregated into a global Figure of Merit to compare the performance of four energy transition technologies: intermittent renewables (iRES), hydro, nuclear, and gas. This aggregation involves summing the individual scores of sub-indicators, each weighted by specific factors, to calculate a final score (S_{global}) representing the technology's performance:

$$S_{global} = \sum\nolimits_{k=1}^{N\_H} \left(w\_H_k \sum\nolimits_{j=1}^{N\_I_k} \left(w\_in_j \sum\nolimits_{i=1}^{N\_S_j} \left(w\_si_i * S\_Si_i\right)\right)\right) \tag{1}$$

where S_Si_i is the score for sub-indicator i (of the indicator j), w_si_j is the weight for the sub-indicator i, w_in_j is the weight for the indicator j, and S_{global} is the final score (the figure of merit for an assessed energy technology). For simplicity, equal weights are applied in Figure 3, since the choice of the weights typically depends on context and is usually defined by policymakers.

A future use of the methodology should benefit from the assigning of weights by relevant stakeholders–such as policymakers, domain experts, or affected communities–through deliberative or participatory processes. This would allow for a more context-sensitive aggregation of sustainability dimensions, better reflecting societal priorities, value judgments, and policy objectives. Incorporating such weighting procedures would enhance the applicability of the methodology in real-world decision-making and improve the legitimacy of the resulting evaluations.

The assessment process showed that the methodology, while complex, effectively captures the diverse impacts of energy technologies, allowing meaningful stakeholder engagement [17]. Results indicated minor performance differences among the technologies (all scoring between 3 and 4), highlighting no clear superior option but affirming their value for energy transition. Gas received lower scores due to environmental concerns and reliance on finite resources, while nuclear scored higher, benefiting from its low emissions and high energy density, biased by the nuclear expertise of the assessment group. Hydro and intermittent renewables (iRES) alternated in second place, with hydro valued for reliability and iRES for sustainability, though each face environmental and resource challenges. Despite current limitations, iRES hold substantial potential, particularly with advances in large-scale storage.

From a detailed perspective on the results, it may be noted there are relevant potential biases in the sustainability assessment process created by the effectivity of several, including divergences in disciplinary perspectives (technical vs. socio-humanistic), the inherent complexity of multi-criteria evaluation, fatigue effects during the assessment, limited time available for reviewing background materials, and the influence of prior convictions regarding the technologies assessed. Future iterations of the methodology may benefit from modular assessments spread over multiple sessions, more interactive or summarized fiches, and optional self-assessment tools to gauge confidence or familiarity with each indicator.

Table 1. Indicators used in the ECOSENS life cycle assessment.

En-LCA	Ec-LCA	Soc-LCA
1.1 Carbon emissions	2.1 Capacity factor	3.1 Jobs created *(with 3 sub-indicators)*
1.2 Land occupation and power density	2.2 Global efficiency	3.2 Impact on the local/regional business (partner with other business)
1.3 Energy returned on investment	2.3 Cost *(with 3 sub-indicators)*	3.3 Additional goods and services created
1.4 Impact on resources *(with 5 sub-indicators)*	2.4 Cost for system integration *(with 5 sub-indicators)*	3.4 Value of the knowledge generated and maintained for the future
1.5 Potential material recyclability	2.5 External costs	3.5 Impact on education
1.6 Emissions, other than Carbon *(with 4 sub-indicators)*	2.6 LCOE Levelized Cost of Electricity	3.6 Contribute to the reduction of inherited burdens (toxic wastes, military stocks)
1.7 Impact on life and ecosystems under normal operation *(with 7 sub-indicators)*	2.7 Macro-economic impact	3.7 Impact on health improvement
1.8 Impact of generated wastes *(with 4 sub-indicators)*	2.8 Applicability for cogeneration	3.8 Impact on poverty
1.9 Impact of accidental situations *(with 2 sub-indicators)*	2.9 Level of standards generated, rules and control *(with 3 sub-indicators)*	3.9 Societal-level adoption of technology
1.10 Mitigation of accidents *(with 3 sub-indicators)*		3.10 Existing investment in RDI to develop the technology
		3.11 Dependency on government support
		3.12 Risks *(with 2 sub-indicators)*
		3.13 Equality of opportunities *(with 2 sub-indicators)*

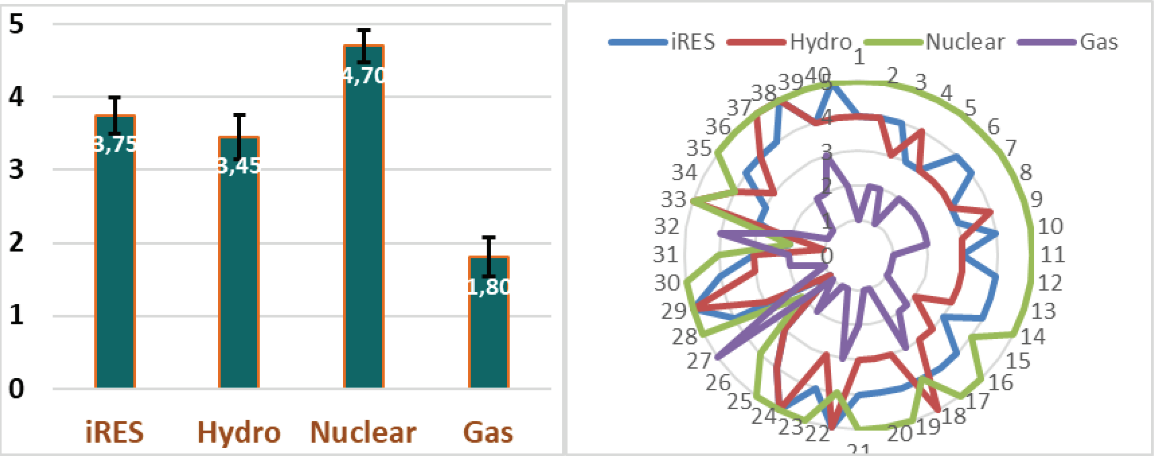

Fig. 2. Assessment results for Indicator 1.1 – Carbon Emissions. The left panel displays the average response value with error bars representing the 95% confidence interval, while the right panel shows the distribution of responses from all 40 participants.

The ECOSENS developed methodology is technology focused and less energy system focused. The value of a technology (Societal, Economic, Environmental) could be dependent on the technology mix of the entire energy system in which it is seated. The methodology may be clearly used in a specific context of a national/regional energy mix with no important adaptation needs, and with a real potential to obtain an agreement on the weights.

Beyond of the previous presented assessment, the role of nuclear power in the future energy market on medium and long term was investigated exploring the possible evolutions at the level of society, and taking in consideration driving factors and obstacles, as well as potential impact of disruptive technologies and different crisis [18]. A critical societal perspective was elaborated through dedicated online and face-to-face workshops involving project partners and stakeholders to discuss and refine these investigations from the societal perspective: *"Decarbonizing Europe's energy system: Checking and choosing indicators for a sustainability assessment"* [19] and *"Decarbonizing Europe's energy system 2: Clarifying non-linear assumptions about energy demand to 2050"* [20].

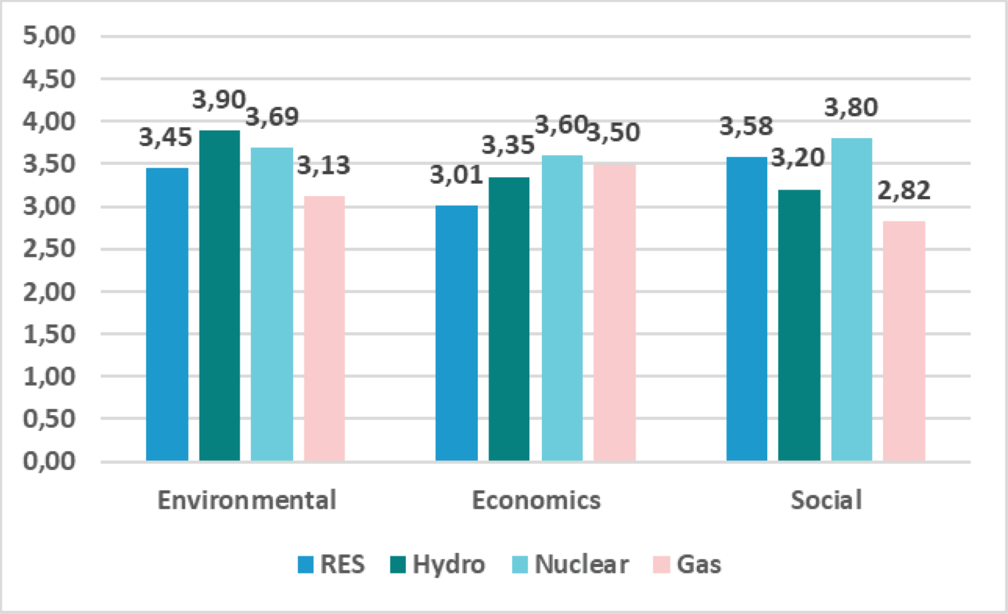

Fig. 3. Figure of merit for the three pillars (Environmental, Economics, Social) of the assessed technologies.

4 A novel economic model

Nuclear energy has long been a subject of intense debate and scrutiny in the global energy landscape. Historically, the deployment of nuclear reactors has not been primarily driven by a return on investment but rather by the intrinsic advantages offered by this technology. These advantages include dispatchable generation, low generation costs, and the potential to foster scientific and industrial development [21]. Despite these benefits, the nuclear energy sector has faced numerous challenges, including public perception issues, safety concerns, and complex regulatory frameworks [22].

In response to these challenges and the evolving energy landscape, the ECOSENS project was proposed to develop and validate a new framework and set of indicators based on the System of Provisions (SoP) approach [23]. This innovative approach aims to enable a comprehensive rethink of energy policy criteria through deliberative stakeholder activities. The SoP approach offers a fresh perspective on the relationship between socio-technical (ST) systems [24], such as electricity, food, and transportation, and nuclear energy. It encompasses both tangible elements, like power plants, and intangible aspects, including culture and workforce education that create provisioning systems [25]. Fine [26] defines in 2002 the provisioning system as "an inclusive chain of activity that attaches consumption to the production that makes it possible". The SoP approach integrates elements from various social sciences (e.g., anthropology and sociology) and focuses on both the "vertical" integration of production and consumption (i.e., the provisioning system) and the "horizontal" societal factors that contextualise consumption. The SoP approach addresses both macro and micro factors related to consumption, making it suitable for analysing universal and global determinants as well as specific contextual factors [27]. In this vein, Mathai et al. [28] point out how the SoP approach enables the investigation of micro (e.g., commodity or value chains), meso (e.g., production networks), and macro levels (e.g., entire economic sectors). The model is developed following Dei et al. [29] in the categorization of the five elements of the SoP approach: agents, relations, processes, structures, and material culture. This categorization allows for a multilevel analysis of nuclear energy systems, distinguishing the roles of public and private stakeholders (agents), supply chain and governance practices (structures), sequences of activities that shape and influence how things are done in social contexts or institutional and market dynamics (processes), interactions and dependencies (relations), and the material and symbolic infrastructure that sustains the nuclear provisioning system (material culture). Through this lens, the ECOSENS model goes beyond economic indicators, offering a grounded assessment of nuclear systems' embeddedness within national political economies and sociotechnical imaginaries.

The novel model developed based on the SoP approach provides a powerful tool for examining energy socio-technical systems and the role of nuclear technologies within them. This approach has proven particularly valuable in the retrospective investigation of nuclear systems across different European countries, offering insights into the complex interplay of factors that have shaped the nuclear energy landscape [30]. By applying this model to study nuclear energy provision, stakeholders, including decision-makers, can gain a more comprehensive understanding of the various agents involved in the provision chain, their priorities, and the intricate interactions between them.

One of the key strengths of the SoP-based model is its ability to identify challenges and opportunities associated with nuclear energy provision. Moreover, it facilitates the development of potential solutions that consider the diverse perspectives and priorities of all relevant stakeholders [31]. This holistic approach is crucial in addressing the multifaceted nature of nuclear energy policy and implementation.

The model, which has been tested and validated throughout the ECOSENS project, serves as a valuable support tool for policy and decision-makers. It enables them to navigate the complex landscape of nuclear energy provision more effectively, considering a wide range of factors that influence the success and sustainability of nuclear energy programs. This comprehensive approach is essential in developing robust and inclusive energy policies that can address the challenges of the 21st century.

Among the tested applications, the model enabled the construction of typologies of national provisioning systems (e.g., state-led, market-led, hybrid), which help contextualize the feasibility of nuclear investments and the types of risks (economic, political, social) they may incur. Such typologies serve as analytical lenses for interpreting national strategies and assessing potential lock-ins or windows of opportunity. Furthermore, the approach was instrumental in revealing the dependencies between industrial capacity, policy frameworks, public discourse, and financial structures, facilitating an integrated policy diagnosis and ex-ante evaluation of deployment scenarios.

A notable feature of the model is its integration of circular economy principles. It considers both the reuse of components and life extension projects as circular economy initiatives, aligning with the growing emphasis on sustainability and resource efficiency in the energy sector [32]. This aspect of the model is particularly relevant in the context of nuclear energy, where the management of resources and waste has been a significant concern.

Furthermore, the model incorporates social financing perspectives, employing a proper social discount rate that reconciles intergenerational equity, environmental impact, and the opportunity cost of money [33]. This approach ensures that the long-term implications of nuclear energy decisions are adequately considered, addressing one of the key criticisms often leveled against nuclear power – its long-term environmental and financial impacts.

The model's efficacy has been demonstrated through its application to case studies in Spain and Romania. These studies have provided valuable insights into the suitability of different national contexts for nuclear technologies. The results indicate that Romania represents an adequate and suitable country for nuclear technologies, presenting an appropriate technological, political, and environmental context. However, the study also highlighted areas needing further improvement, particularly from socio-economic and socio-cultural perspectives.

In contrast, the case study of Spain revealed a more critical scenario, presenting significant challenges across all dimensions, with particular emphasis on socio-cultural aspects. These findings underscore the importance of considering a wide range of factors beyond mere technical and economic considerations when evaluating the potential for nuclear energy deployment. An important insight from the Spanish case was the fragmented public discourse on nuclear energy, marked by polarization and limited engagement of intermediary institutions such as universities or trade unions in the public debate. By contrast, Romania showed stronger alignment between energy policy, institutional support, and socio-technical readiness, although certain local perceptions still require targeted engagement and transparency strategies.

The versatility of this model extends beyond its application in countries with existing nuclear systems. It can also be effectively employed to investigate the suitability of countries for potential nuclear technology deployment. This capability is particularly valuable in the context of global efforts to transition to low-carbon energy sources, where nuclear energy is often considered as a potential component of a diversified energy mix.

In future developments, the ECOSENS model could be further enhanced by integrating agent-based simulations and scenario-building tools. These would enable stakeholders to test the implications of different policy or market evolutions (e.g., carbon pricing, supply chain shocks, financing innovations) on the viability of nuclear options within different SoP contexts.

The development and application of this SoP-based model represents a significant advancement in our approach to nuclear energy policy and decision-making. By providing a more comprehensive and nuanced understanding of the complex systems involved in nuclear energy provision, it enables more informed and balanced decision-making. This is crucial in addressing the global challenges of energy security, climate change mitigation, and sustainable development.

Among the tangible outcomes, the SoP model enabled the identification of mismatches between policy ambitions and institutional capabilities in several national contexts, directly informing strategic recommendations for improving coherence in governance frameworks. Moreover, the model facilitated the creation of a policy tool, a structured decision matrix, that has been piloted in stakeholder forums to rank investment priorities and societal trade-offs in energy technology portfolios.

5 Towards harmonisation in licensing of future nuclear power technologies in Europe

The European Commission has recognized the need to "… *facilitate the establishment of a common understanding on licensing methodologies for advanced technologies between nuclear safety regulators, contributing to harmonisation of licensing methods of future installations*" [34]. In the frames of HARMONISE project it was decided to investigate the potential gaps that may exist in the IAEA documentation. A short overview of project approach and achievements could be found in [35].

The evaluation performed covered high-level IAEA documents such as Safety Fundamentals (SFs), General Safety Requirements (GSRs), Specific Safety Requirements (SSRs) and several selected Specific Safety Guides (SSGs). This review covered safety aspects only and did not consider security issues.

In some part the new reactor concepts are different compared to typical large power light water reactors. Typical differences are:

- Use of an integral and compact design,
- A lower core inventory and lower thermal power,
- Increased use of passive systems,
- A modular design with the possibility of manufacturing entire components in factories,
- A modular plant concept (multi-block units) with common systems (e.g., control room, turbine),
- Transportable or floating SMR & MMR concepts,
- Gen-IV concepts.

The evaluation has been performed covering twenty high-level IAEA documents focusing on nuclear safety issues. The study has taken into consideration both conducted and ongoing initiatives that evaluated document applicability to innovative technologies and SMRs, while it has been complemented with a gap analysis leading to the formulation of proposals for amended as well as novel paragraphs and requirements for the IAEA documentation. The review considered crucial technical aspects such as multi module SMR concepts, factory-built and potentially factory-fueled designs that ought to be transported as well as cogeneration. Functional and technical topics contemplated include the employment of passive systems, consideration of inherent safety in the implementation of the defence-in-depth (DiD) concept, deliberation on the term “core melt”, recognition of the consequences of low-level operating experience, along with facility commissioning, operation and decommissioning.

The performed analysis showed that a set of high-level IAEA documents such as Safety Fundamentals, General Safety Requirements, Specific Safety Requirements and Specific Safety Guides in respect to their applicability to advanced reactor technologies that are currently under development in most aspects as already technology neutral, thus does not require revision. The performed study showed that emerging innovative nuclear technologies do not create a need for new fundamental safety functions. However, their definitions could be reformulated to enable a harmonised applicability to a variety of fission and fusion technology concepts [36,37].

The high-level DiD principles are very well established, technology neutral and seriously affect the safety architecture. The implementation of the DiD principle into the safety architectures depends on the innovative nuclear technology characteristics and the results of the safety analysis. The ISAM supported with extensive R&D promotes diverse views on the safety architecture and it might be considered for the safety assessment of the DiD principles implementation into new designs. TSOs with a strong involvement in R&D activities have the capability to perform a credible and independent safety assessment of the safety architecture.

The ALARA principle is well established as well as technology-neutral. In the logic of the ALARA principle, R&D activities in mitigation strategies and systems must be pursued to minimize the radiation dose to workers, public and the environment.

Finally, passive and inherent safety principles are important constituents of a few emerging concepts and the epicentres of SMR designers. Although both principles are neutral, limited past attention presents important challenges for future legislations. The requirements and criteria needed to prove that a proposed design has achieved a well-balanced safety concept based on the use of the best combination of active, passive and inherent safety features should be defined beforehand and developed accordingly.

It was observed that for different reactor designs, different accident sequences might be relevant and must be postulated. For example, core melt cannot – for all designs – be assumed as the most severe accident, especially not for molten salt reactors with liquid fuel and reactors with TRISO-type fuel. In this matter, the formulation “melting of fuel” or “core melt” is inadequate and needs to be changed to be generally applicable. Proposed terms are “significant core damage”, “significant loss of core geometry”, or “core degradation”. In cases where core melt accidents are eliminated as an initiating event for severe accidents, alternative initiating events that take their place need to be postulated.

While regulatory framework for Light Water Reactors is rather well established and mostly applicable to the innovative nuclear reactor designs a regulatory framework for licensing future fusion power plants (FPP) has yet to be formulated. The work performed in HARMONISE identifies opportunities for efficient and harmonized licensing process of future FPP based on reviewing the existing safety case documentation of fusion facilities at different lifetime phases [38].

The Work Package 2 “*Licensing needs of innovative nuclear power plants*” aims at elaborating recommendations for a common approach to be adopted in evolving the current licensing processes – which are largely based on the technology of large LWRs – towards an harmonised process to be enforced in the future. For this, the WP takes the moves from a review of the safety-related needs which are specific to new reactor technologies (encompassing light-water-cooled SMRs as well as AMRs based on Generation IV technologies, and fusion), which are then compared with the requirements of current regulatory processes, so as to appreciate the extent of their transposability to future technologies in such a way that continuity with the founding safety principles and approaches be secured. In parallel, an analysis is performed of the national regulatory frameworks, to identify commonalities and similarities which could be enforced as foundational in building a harmonised European framework for advanced reactors [39].

In line with the aim of developing recommendations for future licensing processes to be applicable to future reactors, the WP2 started analysing both the needs associated to the technical specificities of advanced reactor technologies, and the foundations of the existing regulatory frameworks. The approach followed reflected the logical organization of the latter, having general principles and requirements set at the highest levels, which in the lower levels are exploded into more detailed requirements and guidelines, which are also progressively more and more technology specific. Accordingly, the WP2 performed at first a survey on the main design and safety-related innovations pursued by the designers of fission and fusion systems in the European context, with an inclusive approach aimed at reaching all the possible technologies considered. Then, an in-depth study was conducted, to better appreciate the impact of innovations on the applicability of current safety frameworks to selected representatives of advanced reactor concepts, namely ALFRED (as representative of an innovative fission reactor) and DEMO (as representative of a fusion infrastructure).

There has been an ever-growing interest since the 1990s in promoting a Risk-Informed and Performance-Based (RIPB) approach to decision making, as an optional alternative of the current, prescription-based process that state authorities apply when licensing and regulating nuclear facilities [40]. Like the current prescription-based approach, the RIPB should comprise capabilities that would assure protection of humans' health, prevent disruption of normal social life, and preclude unacceptable degradation of the environment. Furthermore, the application of the RIPB approach should facilitate the establishment of an effective reactor oversight process and support the selection and prioritization of preventive, protective, and mitigative actions that are optimal for achieving the desired safety objectives for the entire duration of a nuclear facility lifecycle.

The RIPB approach uses the advancements in deterministic and probabilistic safety analyses, the wealth of decades-long operational experience, and insights into human performance under stressful conditions to identify and grade the activities, to carry out the necessary regulatory oversight, to provide the means for comprehensive performance evaluation, and to ensure the achievement of trustworthy assessment results.

Concerns about how confidently one could treat the effect from assumptions, epistemic uncertainties, and biases in risk studies led to a gradual shift since 1990s from risk-based to risk-informed approaches in safety management.

Nowadays, risk practitioners use quantitative outcomes of risk assessment studies just as insights, that do not dominate the conduct of the decision making process but contribute with other considerations to a deliberation process that stakeholders use to work out comprehensive, well-balanced solutions.

The objectives of this deliberation process are:

- To achieve a common understanding of the issues that need resolution,
- To examine the boundary conditions and all assumptions used in the technical studies to establish what possible variations in them might lead to drastically disproportionate, cliff-edge type of changes in the studies' outcomes,
- To outline all other considerations, e.g. social, legal, ethical, financial, and political, etc., which cannot be explicitly addressed by deterministic and probabilistic technical analyses,
- To review all technical analyses and scrutinise their outcomes, e.g. margins to safety limits, statistical distributions of all relevant safety parameters that are impacted by the changes in the already made assumptions as well as initial and boundary conditions.

The presented approach to the deliberation process makes it possible to use the results from all types of technical studies to both: (1) facilitate the integration of non-modelled aspects, e.g. legal, financial, ethical, etc., and (2) reconcile different perceptions of risk.

The traditional approach to safety management relies on the use of deterministic methodologies for safety analysis, which in the facility design focuses on the implementation of sound engineering practices that are part of broadly-acknowledged engineering codes and standards, on the use of engineering margins, redundant features that provide diverse capabilities to prevent catastrophic failures and to contain or mitigate their adverse consequences.

The current regulatory frameworks have demonstrated repeatedly their effectiveness in assuring public safety, but may encounter challenges when having to license the innovative reactor designs, that could utilise innovative nuclear fuel (e.g. molten salt fuel), coolant (e.g. liquid lead, liquid sodium), or include innovative systems that were not licensed before, e.g. Artificial Intelligence in reactor control. There will be a need to develop new approaches to resolve issues, such as:

- Derivation and substantiation of the initiating events and the corresponding accident scenarios for use in establishing all design basis categories.
- Definition of the design and performance requirements of safety-important Structures, Systems and Components (SSCs).
- Evaluation of the contribution to overall safety of individual Defence in Depth (DiD) provisions.

While the outcome from the licensing process appears certain, the effort to license these innovative reactor designs will undoubtedly encounter some serious technical challenges due to the scarcity – or in some cases, even the complete absence – of any operating experience and experimental database.

Many assessments of the capabilities of existing regulatory frameworks to accomplish a licensing review of advanced nuclear reactors within reasonable cost and time constraints have led to the conclusion that a new licensing concept that is "technology-inclusive", risk-informed, and performance-based can serve as a viable alternative to the current set of regulatory processes [41].

In addition to the expected streamlining of the licensing process of the innovative reactor designs, a "technology-neutral" RIPB could contribute significantly to improved understanding by all stakeholders of the risks to individuals, environment, and society from the potential deployment of a large fleet of innovative reactor designs.

One of the WPs in this project deals with the subject from the point of view of codes and standards [42]. Innovative reactor projects call for new technologies based on different and often challenging operating conditions from innovating reactors and require special component

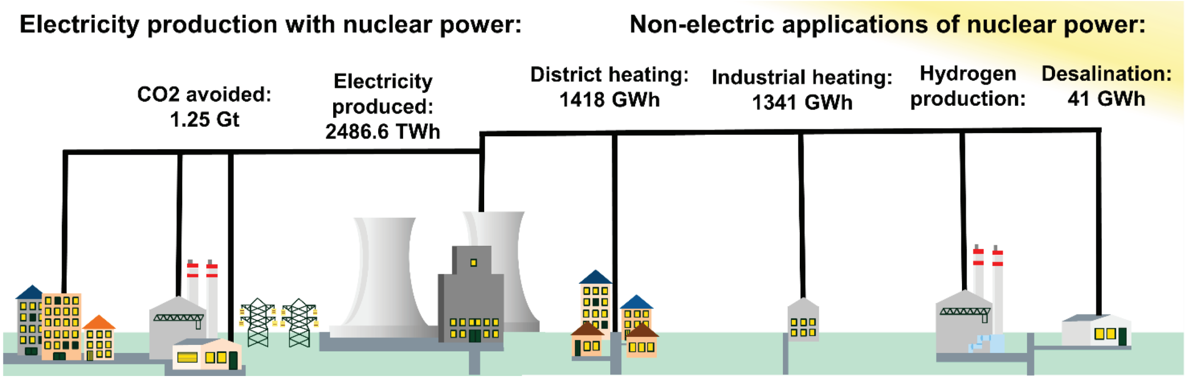

Fig. 4. Scope of nuclear energy electricity production and non-electric uses [43].

designs. These three reasons give rise to new needs in terms of codes and standards that need to be addressed and implemented in a very short timeframe. The work carried out as part of this Project consists, first and foremost, of identifying these needs. To this end, initial data were collected from project partners involved in innovative reactor projects such as DEMO and ALFRED, and a questionnaire was sent to reactor developers, in particular to the many start-ups that have been created in recent years.

These needs are processed to draw up a questionnaire that will be sent to the Standard Development Organisations (SDOs). For the last two categories, the SDOs are expected to provide methodologies. In parallel, the questionnaire will also be sent to other industrial sectors such as aerospace, automotive, rail, etc... In this case, the interest is in seeing how new technologies (essentially digital and manufacturing technologies) have been taken into account and in investigating the possibility to transfer to nuclear field code and standard rules successfully developed.

At the end, a map will be formulated describing the evolution of the codes and standards to fill the gaps and address the development needs identified and implementing the solution options identified. The emphasis will be placed on identifying potential improvements in the harmonisation of codes and standards that could be adopted when the proposed innovations are implemented.

6 Safety assessment of non-electric uses of nuclear energy

Currently there are some non-electric uses of nuclear energy, but they pale in comparison to the scale of electricity production, as seen in Figure 4. This project aims to provide information for industrial applications retrofitted to operating nuclear power plants and for novel reactors dedicated for non-electric uses. Information needs for appropriate risk communication is studied with case studies in several countries, and a specific study on communications during abnormal situations is done based on the events that transpired in Ukraine during Russia's invasion.

The SANE consortium consists of 11 partners from nine European countries (FI, NL, DE, FR, ES, CH, CZ, UA, BE) as shown in Figure 5, and the project is running from September 2024 to August 2027. The work is divided into six major activities, consisting on economic assessment of potential non-electric uses, safety cases for reactors designed for other uses than electricity production, safety of non-electric end uses, studies of risk communication, communications and dissemination, and project management.

The project will assess the potential for non-electric uses of nuclear energy across a wide range of future applications, extending, where feasible, beyond 2050. This assessment includes mapping long-term, large-scale energy demands and evaluating the suitability of nuclear generation to meet these needs. Furthermore, SANE will analyze the current state of knowledge regarding nuclear-renewable hybrid energy systems, examining their opportunities, benefits, technical constraints, safety implications, and relevant modeling techniques.

SANE aims at increasing the overall understanding of the inherent safety merits of non-electricity producing reactor systems, their connection to regulatory aspects such as applied safety criteria and emergency planning zones, and applicability of existing safety assessment tools for these novel, non-electricity producing reactor systems, which may differ considerably from the conventional large-scale nuclear power plants. The nuclear safety authority of Finland has acknowledged this matter and updated the emergency planning zone to permit the deployment of SMRs closer to residential zone on a case-by-case basis [44]. This approach, while enabling new sites for non-electric uses of nuclear energy, also necessitates an improved understanding of the potential consequences of postulated accidents.

The work started through an overall review of safety concepts and criteria, and how they differ between conventional power reactors and non-electricity producing systems. Focus is put into aspects in non-electricity producing reactors that could prove difficult or impossible to consider using the existing safety assessment tools or methodologies, and a number of anticipated operational occurrence (AOO) and design basis accident (DBA) cases highlighting these aspects are identified. The insights

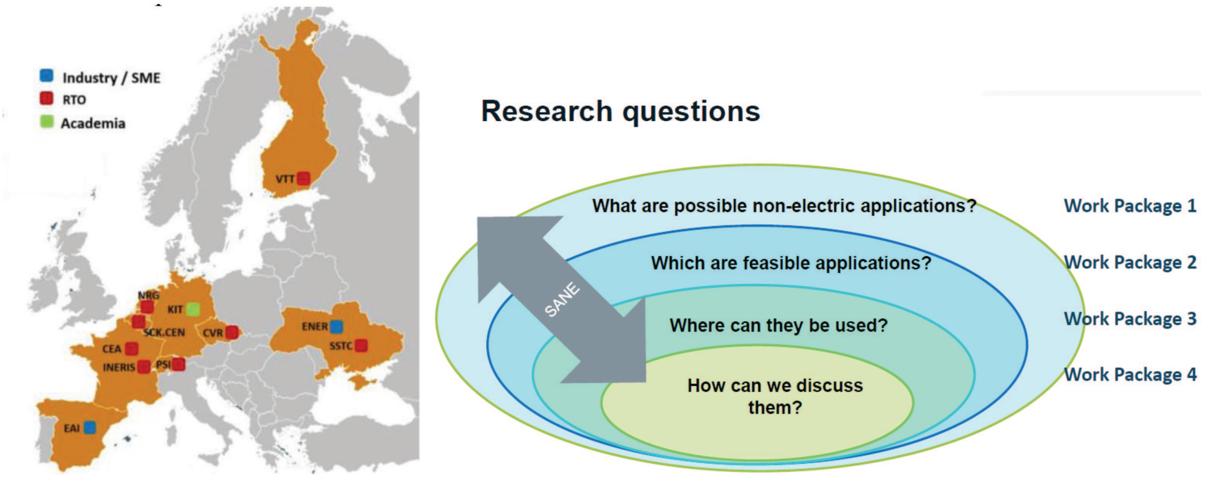

Fig. 5. SANE consortium members and research questions.

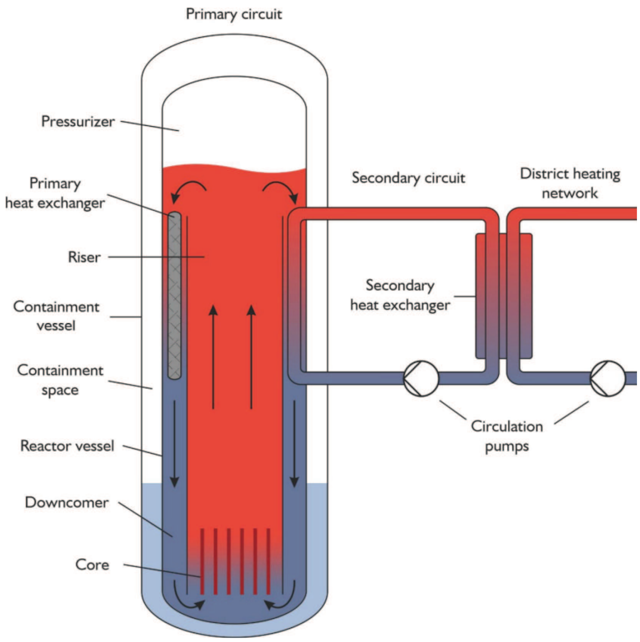

Fig. 6. Schematic outline of LDR lite benchmark reactor. LDR lite is an open definition that approximates the LDR-50 low temperature district heating reactor originally conceptualized at VTT and currently being developed by Steady Energy [45].

gained from this review work are studied in more detail through a set of case analyses comprising of both deterministic and probabilistic considerations.

Given the extensive diversity of non-electricity producing nuclear reactor systems, SANE's focus is specifically on the low-temperature district heating reactor concept, LDR lite, illustrated in Figure 6. This system is considered representative from the point of view of its small scale, heavy reliance on passive safety features, and intended location near a population center.

The feasibility and safety of coupling nuclear reactors with non-electric uses, such as process industry plants, will be investigated using computational modeling tools. Several process industry applications such as district heating, hydrogen production, direct air capture (DAC), agro-industrial applications, and manufacturing of synthetic fuel will be considered. As a highlight, desalination technologies coupled with nuclear reactors are being studied to address global water scarcity specifically in Spain [46]. Various reactor designs (SMRs as well as large LWRs) will be investigated to gain insight into the performance, feasibility, and safety aspects of the coupled system. For example, performance and safety of a solid sorbent-based DAC system coupled to a SMR is investigated with the APROS software [47]. A particular case study is dedicated to the district heat provision to Ukrainian municipalities under the extremely difficult conditions of the Zaporizhzhia nuclear power plant.

SANE aims as well to develop methodologies to improve the state of the art in risk communication related to the operation of NPPs and in particular of SMRs for non-electricity production. The acceptance of the peaceful use of the nuclear energy i.e., for electricity production but also for non-electricity production depends heavily on the risk perception by the general public and decision makers. Hence, the search for proper and effective ways of risk communication arising from the severe accidents from new builds such as SMRs is of paramount importance. A precondition for this is the reliable estimation of the potential radiological risks in terms of the expected dose around the site in the air, soil and water that a person may be subjected to after a severe accident and/or the amount of radioactive material released to the environment. In addition, the risk of SMRs for non-electricity production must be compared with large NPPs and non-nuclear facilities.

The interpretation of risk is not only in terms of the probability of an accident (as is the case of nuclear risk communication in several countries) but also based on the quantification of the corresponding radiological impact on the environment and on the population. As revealed by several studies in the field, experts have usually a lower perception of the risks related to nuclear technologies than the public. Such perception may be further amplified, when novel applications of nuclear energy are envisaged, as SMRs for non-electricity production. Having this in mind, the project aims at building a database including the relevant technical, social, and ethical issues to be tackled.

7 Conclusions

The collective efforts of the ECOSENS, HARMONISE, and SANE projects underscore the critical importance of addressing non-technical dimensions to ensure the accelerated and sustainable deployment of emerging nuclear technologies.

A nuanced understanding of societal perception is paramount. While SMRs are gaining increased political and public attention across Europe, public opinion remains complex and often divided, particularly concerning safety aspects and their ultimate role in the future energy mix. A clear demand for more transparent energy policies exists, and continuous engagement with social actors is necessary to navigate differing views on perceived benefits and challenges.

Furthermore, robust sustainability assessment and economic modeling are essential for informed decision-making and effective public communication. A new, collaboratively developed methodology demonstrates nuclear power's strong overall score in sustainability when assessed across environmental, economic, and social pillars, particularly due to its high energy density and minimal greenhouse gas emissions. The continuous, multi-stakeholder assessment of energy technologies, including nuclear, is vital for adapting strategies to evolving capabilities and market dynamics, ensuring a resilient and flexible energy transition. The insights from a novel economic model, based on the System of Provision approach, offer a holistic pathway to shaping future nuclear policies that integrate broader societal and environmental considerations beyond traditional technical and economic metrics.

In parallel, the evolution of regulatory frameworks is critical. While existing international regulations largely apply to light water SMRs, advanced reactor technologies necessitate a review and potential revision of current guidelines. The HARMONISE project's findings suggest that the existing high-level safety framework provides a viable foundation for a more technology-inclusive approach. This could entail maintaining high-level, technology-neutral safety requirements complemented by technology-specific recommendations, and updating the Risk-Informed, Performance-Based approach to be truly Technology-Inclusive.

Finally, the investigation into non-electrical applications is crucial for broadening nuclear energy's contribution to decarbonization. The SANE project specifically highlights the need for enhanced understanding of the economics, practical implementation, safety issues, and public acceptability of novel applications such as district heating, hydrogen production, and direct air capture. Addressing these aspects, alongside effective risk communication, will be key to unlocking nuclear energy's full potential beyond electricity generation and ensuring its comprehensive role in a sustainable energy future.

By proactively tackling non-technical barriers such as societal acceptance, refining sustainability assessments, developing advanced economic models, and evolving regulatory frameworks to be more technology-inclusive, EURATOM R&D programme is fostering an environment conducive to the safe, secure, and sustainable integration of these advanced nuclear technologies into Europe's energy landscape. This holistic approach, encompassing both societal engagement and regulatory adaptation, is crucial for realizing the potential of SMRs in achieving energy security, independence, and net-zero emissions.

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Conflicts of interest

DD, MC, MD, GD, EU, VT and J-PI certify that they have no financial conflicts of interest (e.g., consultancies, stock ownership, equity interest, patent/licensing arrangements, etc.) in connection with this article.

Data availability statement

Data supporting the ECOSENS results presented in this paper are still under compilation; once finalized they will be deposited in StoreDB.

Author contribution statement

Conceptualization – D.D, E.U, V.T; Writing – Original Draft Preparation, D.D, V.T, EU; Writing ECOSENS chapters – D.D, M.D, C.M, GD; Writing HARMONISE chapter – EU; Writing SANE chapter – VT; Review – D.D, M.C, M.D, GD, E.U, J-P.I; Projects Administration – D.D, E.U, V.T.

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