A generic technology assessment framework for sustainable energy transitions in African contexts

Josephine Kaviti Musango[1, *], John Ouma-Mugabe[2]

[1]Graduate School of Business, University of Cape Town, South Africa
[2] Department of Engineering and Technology Management, Graduate School of Technology Management (GSTM), University of Pretoria, South Africa
[*] Corresponding Author: energytransition21@gmail.com

Abstract

How African countries manage transitions to decarbonised, environmentally and socially acceptable energy systems is a topical issue in public policy, politics and academic spheres today. There is recognition that technology assessment plays a critical role in the choice of specific pathways to just clean energy transitions. Yet, there is limited energy technology assessment practice in Africa. In fact, technology assessment is not well understood and institutionalised. This, in part, is due to the absence of Africa context tailored technology assessment frameworks. This study used an integrated literature review to explore the state and forms of technology assessments and their relevance to energy technology assessment research. The review showed that diverse forms of technology assessments have evolved due to changing priorities in policy, methodological and practical aspects. We propose an action-oriented energy technology assessment that considers geographical contexts, sustainable development dimensions, and different energy systems as dynamic and fosters inclusive stakeholder engagement. The main output of our proposal is a 3-phased generic framework for conducting an energy technology assessments. We conclude that the action-oriented perspective needs to consider a transdisciplinary approach to promote sustainable energy transition and evaluate the sustainability of different energy transition technologies in systemic socio-political and energy contexts.

Keywords: *Energy technology assessment; Energy transition technologies; Sustainable development; Technology assessment; Africa*

1. Introduction

There is an increasing realisation of the importance of just and inclusive energy transitions in achieving the goals of universal access and energy security while decarbonising the energy system. Indeed, the transitions to clean carbon-free energy systems should consider prior prevailing or established socio-economic and energy inequalities and protect jobs in sectors such as mining. This is critical in sub-Saharan Africa, with about 567 million people with no access to 'basic' energy (IEA. et al., 2023, World Bank., 2023) and a majority in natural resource-based sectors such as mining and forestry. Some scholars (e.g. Sokona et al., 2012) have argued that expanding energy access should be an integral part of energy transitions in Africa. Similarly, the Independent Group of Scientists (2019) asserts that promoting expanded access to energy and decarbonisation should be mainstreamed in actions aimed at achieving global Sustainable Development Goals (SDGs).

Several African countries have developed plans and strategies for just energy transitions or embedded energy transition considerations in their climate action policies and plans. There are also increasing investments directed at developing renewable energy technologies. For example, in 2022, South Africa's government adopted the Just Energy Transition Investment Plan (The Presidency., 2023) with a focus on shifting the energy systems away from coal to cleaner forms of energy systems in inclusive and economically sustainable ways, without compromising jobs in the mining sector. Other African countries that have energy transition plans or strategies include Nigeria (Federal Government of Nigeria., 2023), Ghana (Ministry of Energy., 2022), Senegal[1], Egypt, Kenya, Uganda and Rwanda (Sustainable Energy for All., 2022). The countries' plans and strategies recognize the role of technological change in energy transitions. However, there is scant information on specific energy technologies that the countries plan to invest in and how they assess the social, economic and environmental impacts of such technologies. More knowledge about how specific energy technologies can facilitate transformative changes to achieve just and inclusive energy transitions is needed.

Energy transitions are systemic and must be managed to ensure that the transformation of the entire energy system is sustainable (Rutherford and Coutard, 2014). One approach to managing

[1] https://energycapitalpower.com/senegals-energy-transition-a-tale-of-lights-and-shadows/

https://powerafrica.medium.com/shaping-senegals-energy-transition-strategy-4a21f343e265#:~:text=Senegal's%20Energy%20Transition%20Strategy%20details,gas%2C%20over%20the%20long%20term.

energy transitions is undertaking energy technology assessments to gain insights into the potential risks and impacts of new and emerging technologies before their large-scale application. According to Palmedo (Palmedo, 1977: 207), energy technology assessment is "*the systematic evaluation of the implications of alternative technological means to fulfil society's need for energy*". The origins of energy technology assessment can be traced back to the industrial revolution (Palmedo, 1977). For instance, when James Watt and Matthew Boulton analysed the most promising steam engine development options, they conducted a somewhat energy technology assessment with a relatively limited range of concerns and alternatives (Palmedo, 1977). Although historically focused on technology-oriented evaluations, energy technology assessments have evolved to consider the sustainability of energy technologies, which is why some scholars referred it as energy technology sustainability assessment (Musango and Brent, 2011b, Mainali and Silveira, 2015) or sustainability assessment of energy technologies (Grunwald and Rösch, 2011, Carrera and Mack, 2010, Haase et al., 2022).

Prominent studies have developed a variety of frameworks that can support energy technology assessment. These frameworks provide guidelines on how energy technology assessment can be applied to account for different aspects or customised to fit different contexts. Some frameworks focus on improving spatial impacts across the technology life cycle (Karunathilake et al., 2019, Haase et al., 2022). Others consider broadening sustainability dimensions to include social, economic and environmental aspects (Grunwald and Rösch, 2011), while others developed integrated and comprehensive frameworks (Musango and Brent, 2011b, Grunwald and Rösch, 2011). More recently, studies have developed frameworks for assessing emerging technologies and community technology development (Karunathilake et al., 2019). While these studies advance energy technology assessment, a challenge remains in interpreting and implementing the frameworks for policy and practice in the current energy transition technologies. Furthermore, a gap remains about an appropriate energy technology assessment framework that can guide evidence-based policy choices.

Thus, this study explores how technology assessment can contribute to African countries' aspirations to advance sustainable, just and inclusive energy transitions. To achieve this objective, we conducted an integrative literature review to: (i) synthesise the state and forms of technology assessments and justify their relevance to research on energy transition research; (ii) identify emerging issues in the forms of technology assessments to improve their application in Africa's energy transition; and (iii) develop a generic guideline or framework for assessing energy technologies for just and inclusive energy transitions in Africa.

The study contributes to ongoing efforts to implement energy technology assessments in Africa. One such effort is a United Nations Conference on Trade and Development (UNCTAD) project that is assisting three countries, Seychelles, South Africa and Zambia, in sub-Saharan African to (i) assess selected new and emerging technologies that could help them address challenges in energy and agriculture; (ii) stimulate discussion on the economic, social and environmental impacts of the selected technologies; (iii) support national public-sector efforts to access and master some priority technologies for the country (UNCTAD., 2022: 2). This study aims to inform such nascent efforts and contributes to theoretical foundations of technology assessment with and from African perspectives.

2. Method

The study used an integrative literature review to explore how technology assessment can contribute to just and inclusive energy transitions. The integrative literature review assesses, critiques and synthesises literature to generate new theoretical frameworks and perspectives (Torraco, 2016). It covers mature or emerging topics (Torraco, 2016), and the search strategy can be systematic or non-systematic (Snyder, 2019). Technology assessment is a relatively mature topic of academic inquiry and practice, particularly in Europe and the USA, but it is in its infancy in both research and practice in Africa. Therefore, reviewing international practices and experiences with technology assessment is useful to inform energy technology assessments in African contexts. Further, integrative reviews provide a means for probing future practice on a topic (Torraco, 2016). The contribution of this study is to foster future energy technology assessment practice as a decision-support in Africa's energy transitions.

We utilised a non-systematic search strategy and sourced literature from Google Scholar, Scopus, science direct and other websites that provide the evolution of technology assessment in general and with a particular application in energy. The other websites included the US Department of Energy Office of Scientific and Technical Information database (www.osti.gov) and the United Nations Conference on Trade and Development (UNCTAD)[2]. The specific

[2] UNCTAD is currently running a technology assessment in the energy and agriculture sectors with three case studies in Africa - https://unctad.org/project/technology-assessment-energy-and-agricultural-sectors-africa-accelerate-progress-science

search words we used included "*Technology assessment*", "*Technology assessment, AND "Energy",* "E*nergy technology assessment"*, "E*nergy sustainability assessment"*; and "*Technology assessment" AND "Energy transition".* The documents searched included both peer reviewed articles and grey literature. The information we extracted from relevant documents included the state of energy technology assessment in the context of technology assessment scholarship and forms of technology assessment and applications in energy, if any. We further undertook a second review process to specifically identify more examples of technology assessment in energy research in two prominent journals on this topic, *Technology in Society* and *Technological Forecasting and Social Change*. This second search validated our initial observations of the limited use of the term *energy technology assessment* in peer-reviewed journals.

We synthesised emerging issues from the extracted information, which guided the development of a generic framework for energy technology assessment. Shehabuddeen et al. (Shehabuddeen et al., 2000) suggest that a framework may: (i) represent an issue for a defined purpose; (ii) show relationships by linking various elements; (iii) capture a holistic view of a situation; (iv) demonstrate a situation or basis for problem solving; and (vi) provide a structured approach to dealing with a particular issue. Thus, we built on Shehabuddeen et al. (Shehabuddeen et al., 2000, Shehabuddeen et al., 2006) description of a framework as one that 'supports understanding and communication of structure and relationship within [an energy] system for a defined purpose'.

In our study, the structure of the framework is based on the key process elements required to advance each technology assessment approach synthesised from the literature in section 4. These process elements are what Ely et al. (Ely et al., 2014) refer to as "broadening out inputs", which involves extending the scope of each particular technology assessment approach. The framework also depicts the interrelationships of the process elements and how they can facilitate the implementation of energy technology assessment practices in an African context, discussed in section 5. Hence, the frameworks can advance what Ely et al. (Ely et al., 2014) refer to as "opening up outputs", which is the manner in which findings of technology assessment exercises are communicated externally.

To illustrate the potential for implementation of the developed framework, we utilised UNCTAD's technology assessment pilot project, which was launched in Africa with three beneficiary countries, Seychelles, South Africa and Zambia. Our focus was on the South Africa case study, and we showed the potential benefit of the developed technology assessment framework for future energy transition projects.

3. State of scholarship on energy technology assessment

Various scholars have shown that energy technology assessment is not new (Daim et al., 2009, Musango and Brent, 2011a). It has evolved in response to changes in energy systems, policy priorities and global challenges. However, the term "energy technology assessment" is not formalised. Its application continues under the general field of technology assessment, which began in the 1960s in the United States (Berloznik and Van Langenhove, 1998, Tran and Daim, 2008). Philip Yeager coined or framed the 'technology assessment' concept to examine concerns about the effect of technology development on society, human health and the environment (Børsen, 2021a).

Established in 1972, the US Congress's Office of Technology Assessment (OTA) was pivotal in formalising technology assessment. The OTA motivated the widespread institutionalisation of technology assessment in European countries such as France, Netherlands, Denmark, the United Kingdom and the European Union in the 1980s and 1990 (Table 1). Also, health scholars developed health technology assessments to evaluate technology advancement in the field, notable in Europe, USA and, more recently, in Asia.

Although technology assessment is not well established in the African policy space, Mugable and Musango (Mugabe and Musango, Forthcoming) show that the African Union conducted technology assessment-like activities between 2005 and 2007, focusing on biotechnology. These technology assessment-like activities were unstructured and technocratic, conducted by consultants as part of externally funded initiatives (UNCTAD, 2021). Further, many African nations often conceptualise technology assessment-like activities as the identification of unintended impacts or cost-benefit analysis of technologies or infrastructures. Some countries such as Kenya, Namibia, South Africa and Zimbabwe conducted technology assessment-like activities when they were developing their national biosafety frameworks. More recently, with support from the United Nations Conference on Trade and Development, South Africa, Seychelles and Zambia are piloting agriculture and energy technology assessments (UNCTAD, 2019). As part of the pilot project, UNCTAD (UNCTAD, 2021) conducted an exploratory review of technology assessments in Africa. Their review revealed that a few African university scholars have published on technology assessment in the fields of health (Govender et al., 2010, Mueller, 2020) and energy (Musango, 2012, Musango and Brent, 2011b), mainly from doctoral studies. For instance, Kachieng (Kachieng'a, 1999) conducted a health technology assessment study in Kenya and South Africa, while Musango (Musango, 2012) focused on energy technology assessment in South Africa. Despite these efforts, technology assessment in Africa remains unstructured and disconnected from public policy making.

Table 1: Evolution of technology assessment and its applications in the energy sector

Period	USA	Europe	Other countries
1960's	• Philip Yeager coined the term 'technology assessment' (TA) and used it for the first time. • Congressman Emilio Daddario emphasised its relevance in policymaking. Three advisory groups conducted the earliest TA efforts to Congress in the USA – the National Academy of Engineering, the National Academy of Sciences, and the National Academy for Public Administration.		
1970's	• TA becomes synonymous with the Office of technology assessment (OTA) praxis-classical TA. • Development of Health Technology Assessment in 1976.	• Technology assessment was started in Europe with OTA as the role model.	
1980's	• The OTA continues to dominate in the field.	• European countries founded parliamentary technology assessment institutions, including France, The Netherlands, Denmark, the United Kingdom and the European Union. • France: Office Parlementaire d'Evaluation des Choix Scientifiques et Technologiques (OPECST), 1983. • Netherlands: The Netherlands Organisation for Technology Assessment (NOTA) was established in 1986, later renamed to Rathenau Institute. • Denmark: The Danish Board of Technology, 1986. • European Union: Scientific and Technological Options Assessment (STOA), 1987. • United Kingdom: The UK Parliamentary Office of Science and Technology,1989. • Participatory TA (pTA) emerges in Denmark. • Constructive Technology Assessment emerges in the Netherlands. • TA developed as a strategic framework concept, and Germany introduced innovative TA (ITA). • Growth of Health Technology Assessment.	
1990's	• In 1995, the OTA was closed down.	• More European countries established technology assessment institutions, including Germany, Switzerland, Finland, Greece and Norway.	• Privacy impact assessment becomes common.

		• Germany: Office Technology Assessment at the German Bundestag (TAB) in 1991. • TAB transformed into the independent 'Institute for Technology Assessment and System Analysis (ITAS) in 1995. • European Parliamentary bodies established the European Parliamentary Technology Assessment (EPTA) network in 1990. • Interactive Technology Assessment (ITA) became influential and discussed under various names. • Growth in health technology assessment	
2000's	• Congress directed the Government Accountability Office (GAO) to strengthen its TA capabilities in 2002.	• More European countries established technology assessment institutions, including Sweden and Spain. • STOA transformed into 'Panel for the Future of Science and Technology' but retained the acronym. • Growth in health technology assessment.	• Other countries attempt to introduce ethical issues in technology assessment. • UNEP introduces environmental technology assessment (EnTA). • Asia began the initial stages of introducing health technology assessment (e.g. South Korea).
2010's	• GAO established Science, Technology Assessment and Analytics (STAA) in 2019.	• Growth in health technology assessment. • Global Technology Assessment Network (GlobalTA) was established in 2019 and organises conferences every 2 years.	• UNCTAD called for a need for an International Technology Assessment[3]. • Japan established pilot initiatives and institutionalised health technology assessment.
2020's		• Growth in health technology assessment.	• UNCTAD launched a Technology Assessment Pilot Project in Africa with three beneficiary countries: Seychelles, South Africa and Zambia[4]. • UNCTAD report proposed the formation of an Africa Network for Technology Assessment.

Source: Compiled by authors from various sources, including Van Eijndhoven (1997), Palm and Hansson (2006), Coates (2016), Nentwich (2016), UNCTAD (2021) and Børsen (2021a).

[3] https://unctad.org/project/technology-assessment-energy-and-agricultural-sectors-africa-accelerate-progress-science
[4] https://unctad.org/project/technology-assessment-energy-and-agricultural-sectors-africa-accelerate-progress-science

The application of the energy technology assessment to support energy transition policy and decision-making remains fragmented but attributed to the OTA. Before the OTA was closed in 1995 (Palm and Hansson, 2006, Hennen et al., 2023:3), it had conducted several energy technology assessments under various research programmes. Some of the studies explored the potential of nuclear power as a promising new energy technology that could reduce the United States' reliance on oil and gas (Manne, 1976). Some studies also investigated the potential of renewable energy technologies, including solar (Bronfman et al., 1980), decentralised solar in developing countries (Coate, 1980, Larson, 1978), wind (Bollmeier et al., 1980) and geothermal (Cheremisinoff and Morresi, 1976) as a response to the oil crisis in the 1970s. Other studies focused on coal (Kawamura et al., 1979, Chen et al., 1979) and energy-efficient technologies (Piette et al., 1989).

The literature suggests that the bulk of the OTA studies focused on assessing promising new technologies and ways of expanding existing energy technologies, with energy security as the policy priority. Most of the early technology assessment studies had a narrow focus on technical feasibility rather than the socio-economic and environmental impacts of technologies. Despite this limitation, some early OTA energy assessment initiatives, such as those documented in Larson (1978), recognised actors, policies, impacts and technology characterisation as fundamentals of stakeholders' based technology assessment.

Moreso, Bronfman et al. (1983) introduced the concept of community-based energy technology assessment, focusing on technology adoption. Their assessment was relevant to supporting local and municipal energy planning through the involvement of communities. Most notably, Greeley (1986) conducted an energy technology assessment in a rural context. Bronfman et al. (1983) and Greeley (1986) studies demonstrate that energy technology assessment can occur at various scales and the importance of geographical scale or context.

The growing concerns relating to climate change and sustainable development are emphasised in the Brundtland report (WCED., 1987), the Paris Agreement of 2015 (UNFCCC., 2015) and the United Nations Agenda 2030 (United Nations., 2016). These have influenced the priority of energy technology assessment to focus on sustainability issues. Several studies have emphasised the need to assess technological innovations to meet societal energy needs while considering economic, social, and environmental dimensions (Santoyo-Castelazo and Azapagic, 2014, Grunwald and Rösch, 2011, Musango and Brent, 2011b, Truffer et al., 2017).

Thus, the fundamental motivation for energy technology assessment has evolved to deal with the possible short- medium- and long-term consequences of technological innovation. Specifically addressing the societal, economic, ethical and legal impacts as early and comprehensively as possible to enable formative interventions (Grunwald, 2018).

More recently, the need to develop energy systems that are secure, equitable and environmentally sustainable calls for careful management of energy transition technologies. While the literature does not define energy transition technologies, we describe them as the current and future technologies (new, emerging or disruptive) needed for achieving the goals of universal access, energy security and environmental sustainability. The current energy transition technologies are unique because they have become complex, with multiple dimensions to consider (Möller and Grießhammer, 2022). These dimensions are embedded in socio-economic and political structures.

Thus, various scholars (García-García et al., 2020, Healy and Barry, 2017) show the potential implications of energy transition technologies beyond the three sustainability dimensions, hence calling for a just energy transition. The implications include equity, privacy, security and safety, particularly with emerging artificial intelligence, digital technologies, and changes in the market and institutional structures in the energy sector. However, there has been relatively little effort to develop energy technology assessment to support transformative change in energy transitions, particularly in Africa. In addition, although technology assessment originated and is widely known in the USA, Coates (2016) argues that it is virtually unpracticed to inform decision-making. However, most of the current technology assessment activity switched to Europe. Thus, we posit that understanding the various forms of technology assessment in the literature can guide the development of the energy technology assessment field.

4. Forms of technology assessment and their application to energy technologies

Diverse forms of technology assessment have emerged due to practical, methodological, policy priorities and functional aspects attributed to it and adapted to specific contexts (Westermeyer, 1994, Van Merkerk and Smits, 2008). However, there is an evident dearth of consensus among researchers about the forms of technology assessment that exist. This may be due to disciplinary and sectoral fragmentation of technology assessment.

For instance, Van Eijndhoven (1997) identifies four forms of technology assessment that have relevance in energy transitions. These are classical technology assessment, the Office of Technology Assessment, public technology assessment and constructive technology assessment. While Van Eijndhoven (1997) considers the Office of Technology Assessment as a unique typology, we argue that it has similarities with the classical technology assessment. Hence, we categorise it as part of classical technology assessment.

Durant's (1999) study refers to the public technology assessment as participatory technology assessment. Similar work by Børsen (2021b) classified seven technology assessment forms: consequential technology assessment, interdisciplinary technology assessment, ethical technology assessment, hermeneutical technology assessment, participatory technology assessment and constructive technology assessment. We identify the consequential technology assessment as similar to Van Eijhdhoven's classical technology assessment.

Børsen (2021a) suggests different forms of technology assessment that constitute method, process and field oriented. For example, they comprise social impact analysis, environmental impact analysis and risk analysis as "impact-oriented technology assessments". While some scholars consider these the most successful forms of technology assessment (Palm and Hansson, 2006), these assessments are generally not comprehensive. Thus, we consider these to fall under methods of technology assessments rather than forms of technology assessments. Similar to Van Eijndhoven (1997) and Børsen (2021b), Børsen (2021a) also identified other forms, including constructive technology assessment, innovative technology assessment, participatory technology assessment and ethical technology assessment. However, unlike the previous studies, they suggest health technology assessment as a form of technology assessment specific to the medical field. Other forms of technology assessments observed from the reviewed literature include real-time technology assessment (Guston and Sarewitz, 2002), indicative technology assessment (Hammond and Hazeldine, 2015), prospective technology assessment (Möller and Grießhammer, 2022, Liebert and Schmidt, 2010), technology sustainability assessments (Musango and Brent, 2011b, Grunwald and Rösch, 2011) and hermeneutic technology assessment (Nordmann and Grunwald, 2023).

Notably, the previous works have failed to consolidate the different forms of technology assessments that can guide the development of assessment practices in a specific field. An exception we observed in the literature is Børsen (2021a) and Børsen (2021b), who has been developing the practice in Techno-Anthropology. Thus, we argue that advancing energy technology assessment requires more profound insights into the forms of assessments relevant to energy transitions. Drawing from the literature, we summarise ten forms of technology assessment and their definitions, as well as key process elements to advance each assessment approach in Table 2. We further discuss their historical development and their specific illustrations of applications in energy research, if any, in the following sections.

Table 2: An overview of definitions and considerations in selecting forms of technology assessment and applications in energy research

Forms of technology assessment	**Definition**	**Purpose**	**Target audience**	**Stakeholders involved**	**Type of synthesis**	**Possible technology assessed**	**Examples of applications in energy technology assessment**	**Key process elements to advance technology assessment approach**
Classical technology assessment.	"Method for identifying, assessing, publicising and dealing with implications and effects of applied research and technology' (cited in Mills, 2021:4)[5]. "A policy investigation aimed to better understand the implications of the existing, extension of the existing technology or introduction of new technology across society with emphasis on the unplanned and unforeseen effects" (Coates, 2016: 107). "Technology assessment is the systematic identification, analysis and evaluation of the potential secondary consequences (whether beneficial or detrimental) of technology in terms of its impacts on social, cultural, political and environmental systems and processes. Technology assessment is intended to provide a neutral, factual input to decision-making (Coates 1975,	Early warning of impacts or implications. Policy alternative.	Policy.	Engineers, politicians.	Disciplinary / Multi-disciplinary.	Existing.	Dickson et al. (1976); Greeley (1986); Daim et al. (2009). Larson (1978); Cheremisinoff and Morresi (1976); Barrett et al. (1992); Tiemann et al. (2015).	*Make stakeholder engagement inclusive* by broadening stakeholders from exclusively scientific experts to include general public.

[5] Based on the quote from US Congress summaries of activities of the sub-committee on science, research and development 1963-1972. The authors could not retrieve the document.

	cited in Van Eijndhoven, 1997:276).							
Public/participatory technology assessment.	"Assessment directed at public rather than private decision making, and still more appropriately at legislative rather than executive decision making" (Coates 1987, cited in Van Eijndhoven, 1997:278). "Broadly, participatory technology assessment refers to the class of methods and procedures of assessing socio-technological issues that actively involve various kinds of social actors as assessors and discussants" (Joss and Bellucci, 2002:5). "Participatory technology assessment provides advice to policymakers that reflect a wide range of framings, knowledge and values than that derived only from specialists and to encourage wider public debate about future trajectories of socio-technical developments" (Burgess and Chilvers, 2006:713-714).	Foster public debate.	Policy.	Engineers, other experts, citizens.	Interdisciplinary.	New and emerging.	Raven et al. (2009).	*Ensure more inclusive stakeholder engagement* by considering not only political stakeholders but also lay persons. *Promote sustainable development dimensions* by engaging with the controversies of technology. *Take an action-oriented approach* through interactive and creative ways to engage with technology uncertainties and allow learning from diverse stakeholders.
Constructive technology assessment.	"Constructive technology assessment is a new design practice in which impacts are	Broaden design, development and implementation.	Policy	Academia, public authorities,	Interdisciplinary.	New and emerging	Schot (1992); Baumann (2012);	*Advance its application in the energy*

	anticipated, users and other impacted communities are involved from the start, and through interactive manner, contains elements of social learning" (Van Eijndhoven, 1997:280, citing Schot and Rip). Constructive technology assessment "aims to develop better technology in a better society with emphasise on involving a wide range of actors to facilitate social learning about technology and potential impacts"(Genus, 2006:13).		Technology designers and developers.	business and civil society.			Versteeg et al. (2017).	*system* to steer just and inclusive energy transitions.
Real-time technology assessment.	"Real-time technology assessment informs and supports natural science and engineering research, and provides an explicit mechanism for observing, critiquing and influencing social values as they become embedded in innovations" (Guston and Sarewitz, 2002:93).	Builds reflexive capacity within research and development enterprise.	Policy Social sciences	Scientists, social scientists, technologists, General public	Interdisciplinary.	New and emerging	No specific example in energy research was identified.	*Advance its application in the energy system* to help situate technology innovation in its context.
Indicative technology assessment.	"It is a simplified evaluation and illustration of the state of the art of technologies" (Hammond and Hazeldine, 2015:561).	Assess the state of the art.	Academia.	Academia.	Disciplinary.	Existing, new and emerging	Dyer et al. (2008); Hammond et al. (2014); Hammond et al. (2015); Hammond and O'Grady (2017); Hammond et al. (2020).	*Promote inclusive stakeholder engagement* by moving from disciplinary evaluation to translating the knowledge for use to diverse stakeholders.
Technology sustainability assessment.	No single definition, but these are technology assessment studies that consider sustainability or sustainable	Assess the sustainability of technology	Policy. Academia.	Academia, public authorities, civil society,	Interdisciplinary. Transdisciplinary.	New, emerging and existing.	Assefa and Frostell (2007); (Grunwald and Rösch, 2011);	*Develop a generic framework* for

	development as a foundation concept in the assessments. Examples of where the concept is utilised include Grunwald and Rösch (2011), Musango and Brent (2011b), and Mainali and Silveira (2015).	development in a context.		technology developers, technology users.			(Musango and Brent, 2011b) ;(Sala and Castellani, 2011); (Musango et al., 2012); (Yoon et al., 2018); (Haase et al., 2022).	technology sustainability assessment. *Consider context-specific aspects* of integrating sustainability dimensions into energy technology assessment to ensure practical relevance.
Prospective technology assessment.	"ProTA aims to influence technologies by shaping the goals, intentions and attitudes from the perspective of the anticipated consequences and realistic potentials" (Liebert and Schmidt, 2010:114).	Early warning encompassing reflection framework.	Academia.	No.	Interdisciplinary.	Existing, new and emerging.	Möller and Grießhammer (2022).	*Develop a generic framework* for assessing technologies while accounting for the sustainability dimensions. *Integrate sustainability dimension* in the initial stages of technology development. *Broaden stakeholder engagement* by including stakeholders beyond academia.

Interdisciplinary technology assessment.	This is more of an approach to technology assessment that entails collaborative efforts with diverse scientific disciplines to address a societal problem.	Early warning and risk assessment.	Policy Academia	Yes -experts	Interdisciplinary	Existing and new	Cross-cutting	*Make stakeholder engagement inclusive* by broadening stakeholders from diverse scientific experts to collaborate with stakeholders beyond scientific boundaries.
Ethical technology assessment	Ethical technology assessment "gives attention to ethical judgement in technology assessment. It serves as a tool to identify adverse effects of new technologies at an early stage of technology development" (Palm and Hansson, 2006: 543). Ethical Constructive Technology Assessment is concerned with the analysis of the ethical effect of technology at the micro level (Kiran et al., 2015:5). Quick and proper ethical technology assessment is concerned with both intentional and adverse effects (Børsen, 2021a:162).	Assess intended, unintended and cultural implications.	Policy Academia Technology designers	Technology designers	Interdisciplinary	Existing, new, and emerging	No specific example in energy research was identified.	*Advance its application in the energy system* to help assess and support decision making that corrects energy transition injustices.
Hermeneutic technology assessment	According to Nordmann and Grunwald (2023:37), "hermeneutic technology assessment considers the future as it appears in human conversations, popular culture and policy visions, as it appears	Public debate to anticipate narratives, visions and expectations.	Politicians Visionaries	Yes	Interdisciplinary	Non-existent, new and emerging	No specific example in energy research was identified.	*Develop a generic framework* that supports assessing future narratives,

	in calls for proposals and research applications, but also in prototypes and proofs of principle." Hermeneutic technology assessment aims to understand the meaning of emerging technologies in societal discourse (Sand, 2019: 98).							visions and expectations of new and future technologies. *Broaden stakeholder engagement* to support other stakeholders beyond politicians and decision-makers to include technology designers, developers and lay people.

Adapted and expanded by the Authors based on references cited in the table and on Børsen (2021a) and Børsen (2021b).

4.1. *Classical technology assessment*

Classical technology assessment constitutes the original intention of assessments that grew in the 1960s due to increased awareness of the environmental impacts of technology (Coates, 2016). The classical technology assessment anticipates the impacts of technology development to guide public policy and decision-making (Van Eijndhoven, 1997). It aims to assess the adverse effects of a given technology in advance (Schot, 1992, Van Eijndhoven, 1997). The classical technology assessment was further developed to focus more on policy alternatives in technology development and less on early warning (Van Eijndhoven, 1997). According to Van Eijndhoven (1997), the success of these assessments was measured based on the committee primacy principle, stakeholder involvement and quality control of final reports.

Coates (2016: 107) outlines ten steps for undertaking a classical technology assessment: (i) examining problem statements; (ii) specifying systems alternatives; (iii) identifying possible impacts; (iv) evaluating impacts; (v) identifying the decision apparatus; (vi) identifying action options for decision operators; (vii) identifying parties of interest; (viii) identifying macrosystem alternatives (other routes to goal); (ix) determining exogenous variables or events that might be influencing i-viii; (x) draw conclusions and recommendations. According to Coates (Coates, 2016), thirteen key outcomes can emerge from a successful classical technology assessment. These are: (i) modifying the project to reduce disbenefits and/or to increase benefits; (ii) identifying regulatory or other control needs; (iii) defining a surveillance program for technology as it becomes operational; (iv) stimulating research and development to (a) define risks more reliably; (b) forestall anticipated adverse effects; (c) identify alternative methods for achieving technology goals; and (d) identify corrective measures for adverse effects; (vi) identifying control needs; (vii) encouraging the development of technology in new areas; (vii) identifying needed institutional changes; (viii) providing sound inputs to all interested parties; (ix) identifying new benefits; (x) identifying intervention experiments; (xi) delay project; (xii) identifying partial or incremental implementation; and (xiii) preventing technology from developing (an unusual but not impossible outcome).

Examples of classical technology assessment in the energy sector include Dickson et al. (1976) study, which assessed liquid fuel technologies from coal, oil, and nuclear power. Also, Greeley's (1986) study assesses the costs and benefits of windmills and kerosene pumps for irrigation in a developing country context. Other studies include Cheremisinoff and Morresi's (1976) and Barrett's et al. (1992) assessments of geothermal technology and municipal solid waste-to-energy technology, respectively. More recent studies that fall into this category include Daim's (2009) assessment of wind and coal energy technologies and Tiemann's et al. (2015) assessment of shale gas technology in the United States of America.

The classical technology assessment is narrowly focused and rarely assesses emerging technologies. Furthermore, although stakeholder engagement was emphasised in its later developments, the engagement approach was generally a scientific expert-analytic (Sclove, 2010) and excluded the general public. The scientific experts played the role of mediator in this form of assessment (Børsen, 2021b). Therefore, this gave rise to other forms of assessment, such as participatory and constructive technology assessments, which include stakeholders other than scientific experts.

4.2. Participatory technology assessment

Van Eijndhoven (1997) suggests that the participatory technology assessment resulted from the view that controversy about technology was an issue between the government and the public. Technology is generally embedded in society (Durant, 1999) and politically influenced (Joss and Bellucci, 2002). The socio-political characteristics of technology made it crucial to involve the community in technology development decision making. Thus, proponents of participatory technology assessment deemed it as a way of stimulating public discourse, as evidenced by the Danish Technology Board, the Rathenau Institute in the Netherlands and the United Kingdom (UK) Parliamentary Office of Science and Technology (Joss and Bellucci, 2002, Joss, 1998). It has also been applied in Switzerland and Austria (Griessler, 2012).

Participatory technology assessment demands greater involvement of the general public and informed public debate as a precondition for forging socially sustainable public policies (Durant, 1999). Various modes of participation have been used, including citizen panels, scenario workshops and focus groups, which scholars recognised as interactive technology assessment (refer Guston, 2003). Some scholars, however, have argued that expanding the social actor groups involved in political decisions in itself is not enough to achieve better decision-making (Hennen, 1999). According to Hennen (1999), a crucial aspect of participatory technology assessment is responding to the technological controversy in interactive and creative ways, with the issue of uncertainty - scientific, social, ethical, and political - at the heart of modern society. Participatory technology assessment further enables laypeople to develop and express informed judgments concerning complex topics, thus enhancing the social and ethical analysis of technology (Sclove, 2010).

Various studies, including Burgess and Chilvers (2006) and Klüver et al. (2000), have proposed frameworks for participatory processes. In particular, Burgess and Chilvers (2006) conceptual model for designing and evaluating participatory technology assessment accounted for (i) context, including institutional, political, cultural and environmental; (ii) decision situation, which defines the purpose of technology assessment, objectives and inputs; (iii) engagement process which considers whom to be involved, how to engage them and resources needed; (iv) outputs, which are aspects of assessment, decisions and actions; and (v) outcomes, which are material changes that emerges.

Examples of participatory technology assessment in the energy sector include Raven et al.'s (2009) study that assessed new energy technologies with local implementation in five European countries to enhance social acceptance of specific technologies. They utilised a new six-step participatory technology assessment relevant to energy projects at a local level comprising (Raven et al., 2009): (i) project past and present; (ii) vision building; (iii) identifying conflicting issues; (iv) portfolio of options; (v) getting to shake hands; (vi) recommendations for action.

4.3. Constructive technology assessment

Schot and Rip (1997) and other scholars proposed and/or introduced constructive technology assessment in the policy arena, with a primary focus on shaping technology design, development and implementation rather than assessing possible consequences of technology. Constructive technology assessment broadens the focus beyond assessing the impacts of new technologies on the design, development and implementation processes (Schot and Rip, 1997). Its development began in the 1980s and 1990s under the auspices of the Netherlands Organisation for Technology Assessment (Van Eijndhoven, 2000, Schot and Rip, 1997, Rip and Robinson, 2013). The academics, in conjunction with the industry, pioneered its development to respond to the needs of potential users through interactive assessment procedures.

Some studies associate the approach of undertaking constructive technology assessment with Muller in the late 1970s and 1980s in Denmark, which was later advanced in Dutch Technology policy (Schot and Rip, 1997, Schot, 1992, Rip and Robinson, 2013, Van Eijndhoven, 1997) and health research setting (Douma et al., 2007). It was also applied in Norway and Germany, although not initially labelled as such (Schot and Rip, 1997), but it is extensively applied. The Netherlands Organisation for Technology Assessment officially promotes constructive technology assessment.

According to Bertelsen and Petersen (2021), constructive technology assessment can be relevant today because (i) it takes a socio-technical perspective which gives depth to understanding technology; (ii) by assessing technologies, the contextual elements of technology become clear; (iii) it facilitates engaging in a participatory process with key stakeholders; (iv) it provides a framework for addressing technology-related complex issues; and (v) it can emphasise sustainability perspectives in technology development, implementation and transfer.

Børsen (2021b) suggests four criteria for constructive technology assessment, including defining the purpose of the technology; specifying whether the organisation is synchronised to adopt the technology; assessing whether human knowledge is available to operate the technology; and specifying whether the technical elements align with the purpose of the organisation and human landscape.

Examples of applications of constructive technology assessment in the energy sector include Versteeg et al.'s (2017) assessment of the emerging battery technology for grid-connected storage and Schot's (1992) application in renewable energy technologies. It has also been applied to emerging technologies, particularly nanotechnology applications in energy. Despite its limited application in the energy sector, we suggest that it is relevant in helping steer a just and inclusive energy transitions.

4.4. Real-time technology assessment

The literature suggests that Guston and Sarewitz (2002) introduced the concept of real-time technology assessment as a new framework that integrates natural science and engineering investigations with social sciences and policy from the outset into a research program. Tran and Daim (2008) suggest its relevance in assessing emerging technologies.

Real-time technology assessment as an hybrid or variant of other approaches (Ely et al., 2014). According to Guston and Sarewitz (2002), the real-life technology assessment follows a similar general framework as constructive technology assessment but differs in three ways. First, while it shares similarities with constructive technology assessment regarding socio-technical mapping, it does not involve testing new technologies because it is integrated into the knowledge creation process. Hence, it uses reflexive measures such as public opinions, focus groups, and scenario development to elicit value and assess alternative outcomes. Second, it uses content analysis, social judgement research and survey research to investigate how knowledge, perceptions and values evolve in order to enhance communication and identify emerging problems. Third, it integrates socio-technical mapping and dialogue, along with retrospective (historical) and prospective (scenario) analysis. This helps situate technological innovation in its context and can be easily understood and modified if necessary.

Guston and Sarewitz (2002) proposed a mid-level methodology for real-time technology assessment comprising four linked components: (i) development of analogical case studies; (ii) mapping resources and capabilities of the relevant innovation; (iii) eliciting and monitoring changing knowledge, perceptions and attitudes among stakeholders; and (iv) engaging in an analytical and participatory assessment of potential societal impacts. Although real-time technology assessment is pertinent to energy transitions, its application in the energy field is scant.

4.5. Indicative technology assessment

Indicative technology assessments are simplified evaluations and illustrations of the state of the art of technologies (Hammond and Hazeldine, 2015). The origin of the indicative technology assessment is unclear. However, examples of these studies are mainly from an energy technology assessment programme at the University of Bath in the United Kingdom. The studies have focused on energy technologies, including shale gas extraction (Hammond and O'Grady, 2017), hydrogen processing from biogenic municipal waste (Hammond et al., 2020), rechargeable batteries (Hammond and Hazeldine, 2015) and tidal power schemes (Hammond et al., 2014). The indicative technology assessment is relevant to assessing the evolution of new and emerging technologies.

4.6. Technology sustainability assessment

Various studies have explored the concept of sustainability in assessing technology development, referred to in this study as technology sustainability assessments. These studies base their assessments on the Brundtland Report's definition of sustainable development as a development that meets the needs of the present without jeopardising the ability of future generations to fulfil their needs (WCED., 1987).

Although the concept of sustainability emerged in 1987, Möller and Grießhammer's (2022) review article reveals that the culture of technology sustainability assessment is still infant relative to the debates about sustainable development. For instance, Assefa and Frostell (2007) explored the social sustainability of energy technologies. Musango and Brent (2011b) developed a framework for energy technology sustainability assessment which they applied in assessing bioenergy technologies.

There is no universal framework for technology sustainability assessment, and existing studies suggest various general frameworks applicable to a specific case study. For instance, Musango and Brent (2011b) emphasised three key characteristics peculiar to energy technology sustainability assessments: (i) the problem of achieving sustainable development is dynamic and changing over time; (ii) technological development is fast changing; (iii) both technology development and sustainable development require taking a long-term perspective. These characteristics demand developing frameworks and utilising integrated approaches that support action-oriented decision-making for diverse stakeholders. Examples of frameworks developed in the energy sector include Musango and Brent's (2011b) systems approach to technology sustainability assessment (SATSA) framework and Haase's (Haase et al., 2022) E2050 framework using life-cycle analysis. Assefa and Frostel's (2007) study highlights an approach for assessing indicators for social sustainability for energy technologies. Further, Grunwald and Rösch (2011) outlined crucial requirements that must be met for sustainability assessment to have practical relevance in technology assessment. These examples provide insights for integrating sustainability into energy technology assessment in managing energy transitions.

4.7. Prospective technology assessment

The literature suggests that Liebert and Schmidt (2010) advanced the concept of prospective technology assessment as a theoretical extension of the conventional technology acceptance model. Their model encompasses a reflection framework on (i) early-stage orientation; (ii) intention and potential orientation; (iii) shaping orientation – the power/actor dimension; and (iv) orientation towards the technoscientific core. The need for early assessment of technology is emerging, observed in the prospective energy technology assessment. This form of assessment combines the knowledge of the interdisciplinary team to evaluate new energy technology innovations early before the expensive development phase has started. It enables making the effects of the innovation visible and optimises potential products in the early phases.

Prospective technology assessment aims to configure technologies by shaping the goals, intentions and attitudes based on anticipated consequences and realistic potentials (Liebert and Schmidt, 2010). Hence, Möller and Grießhammer (2022) propose framing technology assessment as prospective technology assessment as early as possible, including reflection on the initial phases of technology innovation. According to Liebert and Schmidt (2010), prospective technology assessment requires a normative framework that can be derived from the history of philosophical reflection. Prospective technology assessment is also perceived as a participatory approach, unlike classical technology assessment, which is based on observation from an external perspective.

Möller and Grießhammer (2022) identified four challenges to the application of the prospective technology assessment. These are: (i) understanding the applications of technologies that are beneficial with respect to sustainable development and ones that should be abandoned; (ii) identifying appropriate methods to assess and influence the development of new technologies right from the beginning with sufficient certainty of direction; (iii) identifying who is responsible and competent to perform an evaluation of the sustainability performance of technologies and the corresponding decisions concerning future roadmap; and (iv) identifying ways to transform the technosphere and society into a culture of sustainability. These challenges highlight the importance of integrating sustainability from the initial stages of technology development when undertaking a prospective technology assessment.

Few studies have utilised prospective technology assessments in energy studies since it is still in its infancy. However, Liebert and Schmidt (2015) suggest that its first application was in assessing nuclear technology, and it has broad potential applications in energy research. Further, Möller and Grießhamme's (2022) study proposed it as an approach to transitioning toward a culture of sustainability in the energy sector. They showed how ongoing transformation processes can contribute to the development of the technology assessment framework to advance an agile, goal-oriented and future-proof assessment system.

4.8. Interdisciplinary technology assessment

Some scholars have recognised the interdisciplinary nature of technology assessment. For instance, White (1979) suggests the interdisciplinary approach is crucial in technology assessments because technology related problems cut across disciplinary boundaries. However, as Chubin et al. (1979) show, there are various challenges to interdisciplinary approaches to technology assessment. One challenge is weak interdisciplinary communication as different disciplines tend to have unique ways of research design, research methods and articulating findings.

Since the mid-1990s, some scholars have persistently promoted interdisciplinary technology assessments. For example, Grunwald (1999) presented the ambivalence of technology to revitalise the technology assessment and emphasised the need for early warning assessment in relation to technological risks. Risks are generally invisible and require a scientific lens to identify them; hence, Grunwald (1999) argued for expert engagement from diverse disciplines. Thus, interdisciplinary technology assessment emphasises the necessity for collaboration beyond disciplinary borders in evaluating technologies.

Interdisciplinary technology assessment is particularly relevant in energy transitions where ambitious targets for technology development require simultaneous collaboration across disciplines as well as stakeholder engagements beyond scientific boundaries. Cohen et al. (2021) suggest defining common objectives and allowing each discipline to retain its distinctive approaches when tackling the challenges of interdisciplinary energy research. Therefore, interdisciplinarity aims at integrating disciplines, co-developing knowledge and setting a common goal for technology assessment. Although Børsen (2021b) identifies interdisciplinary technology assessment as a form of evaluation, we suggest that it is more of an approach to assessment.

4.9. Ethical technology assessment

Ethical technology assessment emerged due to ethical questions raised from new technology development. The assessment gives attention to ethical judgement in technology assessment. The literature suggests that Palm and Hansson (2006) introduced the ethical technology assessment. Other scholars, such as Børsen (2021b), suggest ethical technology assessment as a variant of interdisciplinary that evaluates not only the intended consequences but also includes possible unintended consequences and cultural implications. Hence, it directs responsible innovation and ethical design. Børsen (2021a) refers to it as an impact-oriented technology assessment focusing explicitly on the ethical impacts of new technologies.

Palm and Hansson (2006: 555) developed a nine-point checklist of ethical concerns against which to assess technologies. These were: (i) dissemination and use of information; (ii) control, influence and power; (iii) impact on social contact patterns; (iv) privacy; (v) sustainability; (vi) human reproduction; (vii) gender, minorities and justice; (viii) international relations; and (ix) impact on human values. While these checklists are largely about the impacts of technologies, they bring to the attention energy justice issues pertaining to gender, minorities and justice, which are still overlooked in current energy technology assessment practices.

Other studies have also developed variations of ethical technology assessments. For instance, Kiran et al. (2015) proposed an ethical constructive technology assessment that guides assessing technologies and integrating ethical reflections in technical design processes. Børsen (2021a) recently developed a quick and proper ethical technology assessment for techno-anthropologist to assess real or imagined ethical issues in socio-technical systems. Despite the differences in these studies, they aim to integrate ethical aspects into technology assessment. Their main difference lies in the scope of analysis and included factors. Ethical technology assessments occur at macro and meso levels, while ethical constructive technology assessment deals with intentional effects at a micro level. On the contrary, quick and proper ethical technology assessment includes both intentional and adverse effects.

Scholarly interest in addressing ethical issues in energy transition has been growing (Miller, 2014, Kumar et al., 2021). For instance, according to Miller (2014), energy transition raises significant ethics and justice concerns around reorganising energy production, consumption and redistribution of power, wealth, risk and vulnerabilities. Thus, ethical energy technology assessment has the potential to assess and support decision making to correct energy transition injustices. However, there is limited evidence of ethical technology assessment in the energy sector.

4.10. Hermeneutic technology assessment

Hermeneutic technology assessment is attributed to Grunwald (2020, 2023). He developed it to consider knowledge about an uncertain future when dealing with emerging technologies and extends the hermeneutic aspect of technology assessment (Sand, 2019). According to

Nordmann and Grunwald (2023), hermeneutic technology assessment considers the future as it appears in human conversations, popular culture and policy visions, as it appears in calls for proposals and research applications, but also in prototypes and proofs of principle. Thus, hermeneutic technology assessment attempt to tackle the difficulty of evaluating the consequences or implications of non-existent, new or emerging technologies, which are unknown. It requires knowledge of the respective context, including motivations, perceptions, attitudes, values, interests of actors and messages of future narratives and their interpretations (Grunwald, 2020).

According to Børsen (2021b), hermeneutics technology assessment is anticipatory and focuses on future narratives, visions and expectations about new or future technologies. It is, therefore, relevant to technologies when no valid knowledge, predictions or scenarios exists about the implications and consequences of technology. This form focuses on advising politicians and decision makers, and not technology designers and developers.

Despite its potential to assess new and emerging technologies, how hermeneutic technology assessment can provide the answer to challenges of technology assessment remains an open question. Its application and empirical cases are still limited, but Nordmann and Grunwald (2023) propose its potential application in nanotechnologies, which are emerging technologies that have attracted technology assessment in the last 20 years. Furthermore, Sand (2019) suggests an important question ask is the kind of knowledge created and whether and how it is relevant for policymaking. This kind of knowledge is necessary for advancing energy technology assessment in energy transitions.

5. Advancing energy technology assessments in Africa

This section addresses the second question of this paper on emerging issues in the forms of technology assessments to improve their application in Africa's sustainable energy transitions. Although the forms of technology assessment discussed in section 4 differ in the perspective and evaluation options, they are fundamentally rooted in supporting decision-making in managing technology development. Hence, they are relevant in the management of different technology-based energy transitions. However, because current technology assessment approaches have been designed and applied mainly in Europe and the USA, they need to be adjusted to African contexts based on specific goals and targets of energy transitions.

The African Union (AU) Agenda 2063, the SDGs and the Paris Agreement Climate change provide overall policy priorities and frameworks for energy transitions in Africa. In 2019, the Africa Union (AU) adopted the African Energy Transition Programme being coordinated by the African Energy Commission.[6] There is no explicit provision for technology assessment in the Programme, though reference is made to "implementation of a systematic, continent-wide approach to innovation to harness the research and development capacities" that can be invoked or interpreted to undertake energy technology assessments. There are no specific technologies that the AU has identified for implementation to achieve the 'African energy transition'. Perhaps this is because different African countries have different energy systems and needs as well as scientific and technological capabilities to engage with different energy technologies. Some countries, such as South Africa and Namibia, have identified green hydrogen as a key new source of clean energy, while others, such as Botswana, are focused on the expansion of solar energy.

One would expect that there is a formal technology assessment framework to drive policy discussion and formulation of energy transitions strategies and practices in Africa. Certainly, no formal, public and transparent energy technology assessments are available that explicitly address the energy systems.

Taking into consideration of the various forms of technology assessment reviewed and the policy priority of Africa's energy transition, we redefine energy technology assessment as *a deliberate endeavour to assess the potential and impacts of technological change [technology development] in an evolving energy system [dynamic system] to advance sustainability, design selection and utilisation of resources [sustainable development]*.

At a practical level, it is possible that any of the forms of technology assessment discussed in section 4 can be relevant for assessing energy technologies based on selection criteria set out in Table 2, which include: (i) purpose of technology assessment; (ii) target audience; (iii) stakeholder engagement; (iv) type of synthesis; and (v) possible technology assessed. However, we further argue that technology assessment of energy transitions technologies can be improved by taking an action-oriented approach. The action-oriented energy technology assessment builds from the previous forms of assessments by accounting for the key process

[6] https://au-afrec.org/energy-transition-programme

elements to advance each approach. For example, it is revealed from the literature that inclusive stakeholder engagement is an underlying element necessary to advance most forms of technology assessments. We thus describe an action-oriented energy technology assessment as shaped and reshaped through an inclusive stakeholder engagement process in a social setting rather than first being theorised and then translated into practice as often done in the previous technology assessment practices. We argue that an action-oriented energy technology assessment needs to bring diverse stakeholders who share a common interest in the role of social and political action for energy technology change. In addition, while it builds upon the existing diverse technology assessment perspectives, it focuses on the key process elements required to advance each of the technology assessment approaches, summarised in the last column of Table 2. Four process elements we synthesised and visualised in Figure 1 include: (i) geographical scale of analysis or context; (ii) sustainable development dimensions as fundamental in energy technology assessment; (iii) energy system under consideration; and (iv) inclusive stakeholder engagement beyond participation. These elements are interrelated in how they inform action-oriented energy technology assessment, and we represent the form of assessment that may be required as phases 1 to 3 in Figure 1. The three phases are sustainable energy transition (Phase 1), sustainability assessment of energy system (Phase 2) and energy transition technology assessment (Phase 3). These three phases allows for practical implementation and shaping and reshaping the technology assessed for achieving sustainable transitions, which we discuss in Section 6. We discuss each of the four process elements as emerging issues in the section that follows.

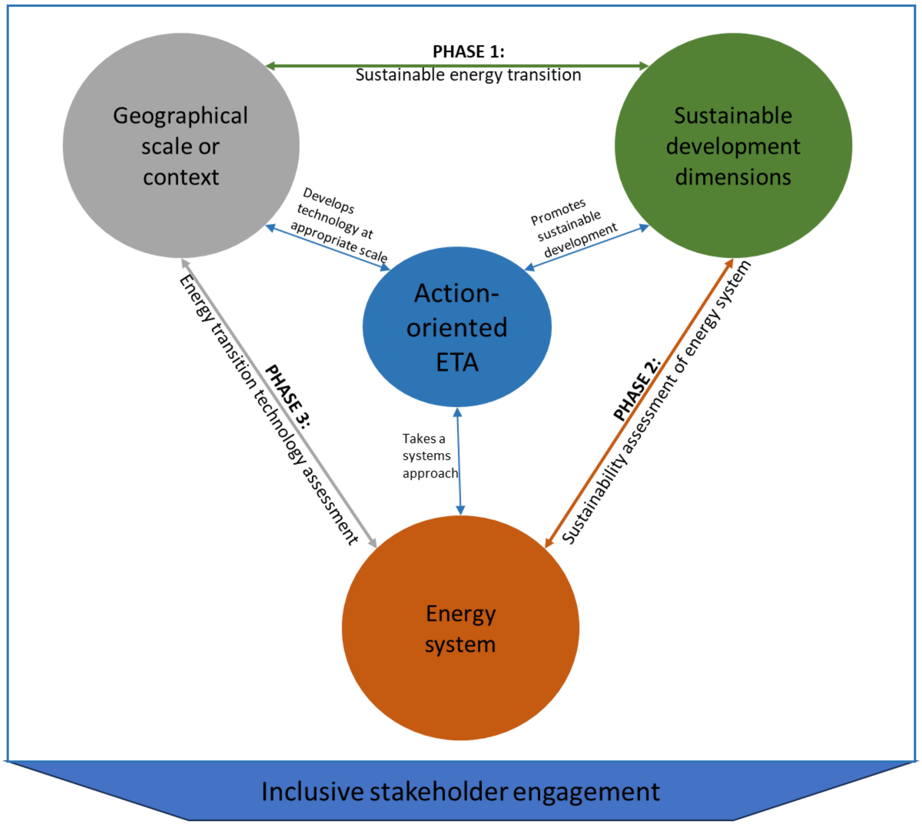


Figure 1: Action-oriented energy technology assessment framework

Source: Authors

Note: ETA is energy technology assessment

5.1. *Geographical scale of analysis or context*

Various scholars highlight the importance of differentiating content and context in technology assessment (Schot, 1992) and energy transitions (Thomas and Erickson, 2021). This is because technology assessment is embedded within socio-political, socio-cultural and spatial realities. The literature shows that technology assessment is dependent on the social, economic, cultural, political and institutional context. However, there are no coherent energy technology assessment practices in Africa (Musango and Brent, 2011b, UNCTAD., 2022, Fox and Griffy-Brown, 2023).

Thus, three possible issues emerge related to geographical scale or context. First, the existing approaches to technology assessment are not suited for the diverse scale of analysis and are narrowly framed for assessments at a national scale. New and emerging energy technologies are likely to disrupt the current institutional and market structures. Thus, the energy transition can occur at various scales, including regional, national, urban and household / firm levels. Hence, energy technology assessment needs to account for various scales of assessment.

Second, existing forms of technology assessment may not directly apply to Africa's energy transition due to the context in which they were developed. Most of the existing forms of assessments emerged in the Western context and are not suitable for the heterogenous contexts in Africa, where governance structures for participatory decision-making are weak. Third, the sustainability dimensions for technology assessment differ based on the scale of analysis. Thus, recognising the geographical scale enables establishing the context for sustainable energy transition before undertaking the assessment.

5.2. Sustainable development as a fundamental framework in energy technology assessment

Ensuring energy systems sustainability has become one of the pressing issues for policy and decision makers globally (Santoyo-Castelazo and Azapagic, 2014). For instance, IRENA and Africa Development Bank's (2022) recent report stipulates that Africa's energy transition is to drive the sustainable development of the continent. Therefore, technology assessment of energy transition must consider sustainability as fundamental. On the one hand, the increasing concerns about the impact of climate change have led to the definition of society's long-term sustainability vision that focuses on reducing emissions in the energy sector (Nakata et al., 2011). This interpretation of sustainable development has evolved since its inception in 1987, and it is becoming increasingly relevant to considerations for developing and evaluating energy transition technologies. In particular, SDG7 aims to accelerate efforts worldwide to access affordable, sustainable and modern energy for all. On the other hand, most of the forms of technology assessment emerged before the concept of sustainable development became dominant and the adoption of the 17 SDGs. Thus, the challenge with existing forms of technology assessments is how to integrate into them sustainability considerations. Existing technology assessment approaches are not capable of dealing or covering inter-generational uncertainties.

Various studies show how sustainability assessment discussions have evolved significantly. However, the culture of integrating sustainable development in technology assessment remains limited (Möller and Grießhammer, 2022, Brent, 2012). As sustainability is a fundamental aspect of energy transition in Africa, we suggest a framework that adapts to changing energy systems. While the environmental dimension of global emissions continues to influence sustainability assessments in energy technology development, sustainability assessments of energy transition technologies also require considering the socio-economic, ethical and socio-political aspects. Grunwald and Rösch (2011) suggest an integrative approach to sustainable development meeting three criteria: (i) a *clear object relation* articulating the subjects attributed to the assessment; (ii) *power of differentiation* that clarifies what sustainability or unsustainability ascribed to the society or development need to be made possible; and (iii) the possibility to *operationalise* requiring indicators to determine target values and empirical measurements of sustainability. Musango and Brent (2011b) also suggest a framework that combines both technology assessment and sustainability assessments in a dynamic energy system. The implication is that a flexible and adaptable framework is essential for guiding technology assessments in energy systems in transitions.

5.3. Energy system under consideration

Supporting the choice of technology and/or investments in technology development within an energy system is one of the critical aims of technology assessment. Energy systems represent the relationships between the production and consumption of energy services necessary for human activities within a society (Nakata et al., 2011). The boundary of an energy system circumscribing these activities may differ in geographical and sectoral scopes. The system may correspond to an entire society ranging from a single village to a group of countries and may consider a single group of activities or multiple sectors. The energy system encompasses energy sectors, projects and energy services and thus entails the factors, functions and activities that influence the transformation processes between the different states of energy (Nakata et al., 2011).

Therefore, energy systems are not exclusively technical and constitute socio-technical aspects, including actors, policies, institutions and decision rules (Larson, 1978, Karunathilake et al., 2019). The technical aspects may include technology characterisation – new, emerging or existing technology performance and technical viability. In addition, energy systems generally change over time, characterised by uncertain new and emerging technologies. Many forms of technology assessments are appropriate for new and existing technologies but unsuited for disruptive or emerging technologies. Further, Witmayer et al. (2020) indicate the social dimension of sustainable development continues to be neglected in energy systems. This suggests the growing need for including stakeholder engagement to integrate socio-technical aspects of technology development and their associated uncertainties.

5.4. Inclusive stakeholder engagement beyond participation

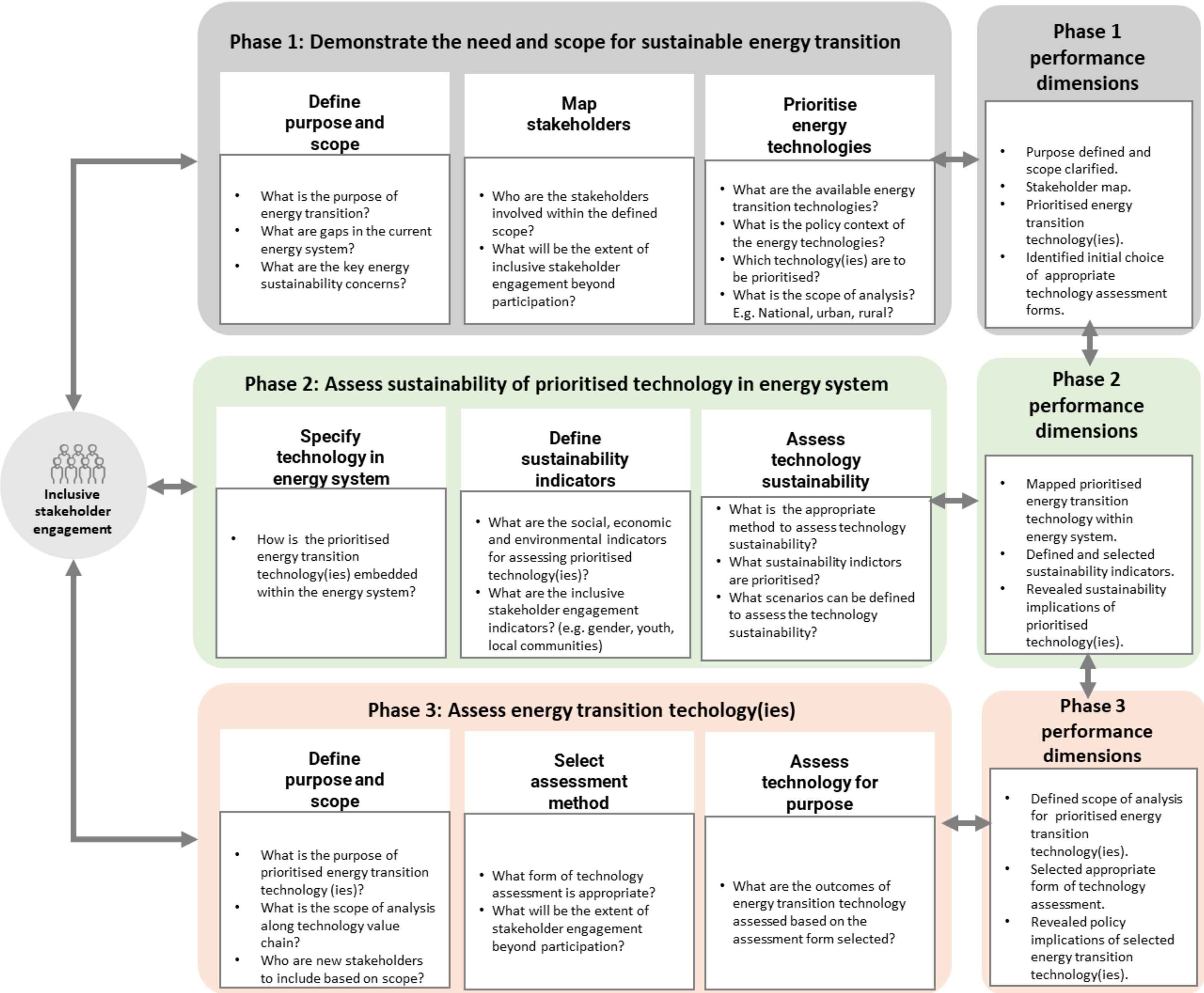
Integrating knowledge from diverse stakeholders is an essential role of technology assessment. The reviewed forms of technology assessments are thus increasingly advocating for participatory and inclusive processes with key stakeholders organised in an interdisciplinary approach. These approaches are geared toward identifying the most sustainable and resilient pathways for energy transition technologies within the energy system. However, the extent of stakeholder participation continues to receive criticism about the inclusivity of the stakeholders. In particular, gender mainstreaming is excluded from technology assessment practices, yet it is an important aspect relevant to sustainable energy transition. Additionally, youth represent a majority of the population in Africa and the energy transition needs of the population differ according to the scale of analysis. For instance, the urban energy needs of high-income households are different from those of households living in informal settlements and those in the rural context. Further, the gender dimension is critical to understanding the different energy needs of women and men and how they impact technology development. Hence, we propose integrating the gender dimension in energy technology assessment in order to design gendered energy systems. Therefore, a transdisciplinary approach is necessary in order to analyse the possibility of such transition and support assessment. The approach brings together multiple perspectives of non-academic stakeholders, scientific disciplines, as well as the resulting interactions among the sustainability dimensions – economy, society and the environment (Nakata et al., 2011, Fazey et al., 2018).

6. Proposed framework for implementing an action-oriented energy technology assessment in Africa's energy transitions for sustainability

This section addressed this study's third question by proposing a generic framework for assessing energy technology in managing Africa's energy transitions. Energy transitions in Africa to achieve universal clean energy access without disrupting existing economic activities in sectors such as mining are expected to occur at multiple scales, involving multiple stakeholders. It is also expected to be influenced by diverse socio-political contexts as well as countries' prior established techno-economic infrastructures.

The quest for a holistic approach to technology assessment is a misconception because any of the forms of technology assessment supports a particular segment of the technology development phase and one type of assessment might be more relevant/appropriate in other stages. Hence, in Figure 2, we propose a generic 3-phased framework for implementing an action-oriented energy technology assessment to enhance the assessment of technologies for Africa's energy transitions. These three phases were informed by the process elements discussed in section 5, requiring action to: (i) demonstrate the need and scope for sustainable energy transition (Phase 1); (ii) assess sustainability of prioritised technology in the energy system (Phase 2); (iii) assess energy transition technology(ies) (Phase 3). Although the phases are presented linearly, they are generally iterative, constituting an inclusive stakeholder engagement in a transdisciplinary approach.

In discussing the three phases, we utilise UNCTAD's project piloting energy and agriculture technology assessment to enrich the extent to which the proposed generic framework can be actioned in an African energy transition project. We focused on UNCTAD's case study on South Africa energy technology assessment because the authors were engaged in the project. UNCTAD developed and proposed a methodology for technology assessment in developing countries, which they were piloting in the energy and agriculture sectors to accelerate progress in science, technology and innovation. Hence, the authors' engagements in UNCTAD's pilot project enhanced insights into the proposed framework for an action-oriented energy technology assessment.



Phase 1: Demonstrate the need and scope for sustainable energy transition
Define purpose and scope
• What is the purpose of energy transition?
• What are gaps in the current energy system?
• What are the key energy sustainability concerns?
Map stakeholders
• Who are the stakeholders involved within the defined scope?
• What will be the extent of inclusive stakeholder engagement beyond participation?
Prioritise energy technologies
• What are the available energy transition technologies?
• What is the policy context of the energy technologies?
• Which technology(ies) are to be prioritised?
• What is the scope of analysis? E.g. National, urban, rural?
Phase 1 performance dimensions
• Purpose defined and scope clarified.
• Stakeholder map.
• Prioritised energy transition technology(ies).
• Identified initial choice of appropriate technology assessment forms.
Inclusive stakeholder engagement
Phase 2: Assess sustainability of prioritised technology in energy system
Specify technology in energy system
• How is the prioritised energy transition technology(ies) embedded within the energy system?
Define sustainability indicators
• What are the social, economic and environmental indicators for assessing prioritised technology(ies)?
• What are the inclusive stakeholder engagement indicators? (e.g. gender, youth, local communities)
Assess technology sustainability
• What is the appropriate method to assess technology sustainability?
• What sustainability indictors are prioritised?
• What scenarios can be defined to assess the technology sustainability?
Phase 2 performance dimensions
• Mapped prioritised energy transition technology within energy system.
• Defined and selected sustainability indicators.
• Revealed sustainability implications of prioritised technology(ies).
Phase 3: Assess energy transition techology(ies)
Define purpose and scope
• What is the purpose of prioritised energy transition technology (ies)?
• What is the scope of analysis along technology value chain?
• Who are new stakeholders to include based on scope?
Select assessment method
• What form of technology assessment is appropriate?
• What will be the extent of stakeholder engagement beyond participation?
Assess technology for purpose
• What are the outcomes of energy transition technology assessed based on the assessment form selected?
Phase 3 performance dimensions
• Defined scope of analysis for prioritised energy transition technology(ies).
• Selected appropriate form of technology assessment.
• Revealed policy implications of selected energy transition technology(ies).

Figure 2: Proposed 3-phased framework for implementing an action-oriented energy technology assessment for sustainability

Source: Authors

6.1. Phase 1: Demonstrate the need and scope for sustainable energy transition

The first phase (phase 1) establishes the energy transition contextual issues and the breadth of assessment underpinned in a sustainability perspective. This phase applies to all forms of technology assessments as it is necessary to establish the purpose and scope of the energy transition, map the stakeholders, and prioritise energy technologies. In defining the purpose and scope, the key questions asked include: what is the purpose of energy transition? What are the gaps in the current energy system? What are the key sustainability concerns? Mapping the stakeholders guides the understanding of the extent of inclusive engagements, requiring asking questions such as: Who are the stakeholders involved within the defined scope? What will be the extent of engaging the stakeholders beyond participation? Prioritising energy technologies, helps in discussing the possible energy transition technology(ies) or related converging pathways, and includes asking the following questions: What are the available energy transition technologies? What is the policy context of the energy technologies? Which technology(ies) are prioritised? What is the scope of analysis?

Thus, phase 1 guides the initial choice of the appropriate form of technology assessment and the relevant issues for consideration. It is also possible that more than one form of technology assessment can be undertaken in a project to complement each other. This is critical because there is no singular pathway but plural pathways to sustainability in energy and socio-economic systems. Indeed, inclusive and just energy transitions are attained through multiple socio-technical changes. Four performance dimensions of phase 1 to monitor progress are to check if the purpose is defined and clarified, a stakeholder map is established, energy transition technology is prioritised, and initial appropriate assessment forms are identified.

Several aspects of Phase 1 were incorporated into the South Africa energy technology assessment case study. However, it was not in the order presented in our proposed 3-phased framework. For instance, the purpose and defining of goals was towards the end of the project rather than at the beginning of the project. Hence, little was known about the requirements of technology assessment. In addition, although stakeholder mapping took place, this was later in the process. Hence, key stakeholders were excluded from the beginning of the project. For instance, the Department of Minerals and Energy was not involved, yet the project was influencing energy issues. Similarly, other key stakeholders not engaged in the pilot study included the Department of Agriculture and Department of Tourism. The pilot project was mainly driven by a steering committee that was established and a number of scientific experts.

This somewhat exhibited elements of classical technology assessment, which relies on scientific experts.

The technology prioritised was green hydrogen electrolysis, but the steering committee and scientific experts influenced the choice of technology. However, the existing energy policy developments driving energy transitions in South Africa, which is becoming a global player in green hydrogen, influenced the technology choice.

The pilot study applied a pre-determined UNCTAD methodology, which did not consider the need to select an appropriate technology assessment method. Hence, there was a lack of clarity on the appropriate approaches and the methods used to assess the technology, which relied on ad-hoc focus group workshops and expert interviews.

6.2. Phase 2: Assess the sustainability of prioritised technology in the energy system

The second phase (phase 2) informs decision making on the appropriate sustainability dimensions and prioritised indicators of the identified energy transition technology, taking a systems perspective. It involves specifying technology in the energy system, defining sustainability indicators and assessing technology sustainability. In specifying the technology in the energy system, the question asked is: how is the prioritised energy transition technology(ies) embedded within the energy system? In defining sustainability indicators, it is important that the indicators cover the three dimensions of sustainability, namely, society, economy and environment. Further, dimensions for inclusive stakeholder engagements are crucial and include gender, youth and local community knowledge. The questions asked to drive action in defining indicators are: What are the social, economic and environmental indicators for assessing prioritised technology(ies)? What are the inclusive stakeholder engagement indicators? Assessing technology sustainability involves selecting an appropriate method and undertaking an assessment that informs decisions on the trade-offs and impact areas in the three sustainability dimensions. It involves asking questions such as: what is the appropriate method to assess technology sustainability? What sustainability indicators are prioritised? What scenarios can be defined to assess the technology sustainability?

Thus, phase 2 guides the refinement of the form of technology assessment and the choice of appropriate methods and indicators for sustainability assessment. The key performance indicators dimensions in phase 2 include mapped prioritised energy transition within the energy system, defined and selected sustainability indicators, and revealed sustainability implications of prioritised technologies.

Limited work was done to incorporate aspects of phase 2 in South Africa's energy transitions technology assessment project. Although green hydrogen was identified as the prioritised technology, it was not mapped within South Africa's energy system. The focus was mainly on the technology rather than consideration of the sustainability implications of the technology. However, the project provided the policy context in Phase 1, which situated the historical policy development and current policy development supporting the prioritised technology.

6.3. Phase 3: Assess energy transition technology(ies)

In the third phase (Phase 3), the assessments inform decision making in technology design and development in an evolving energy system while considering sustainability aspects prioritised in Phase 2. Phase 3 conducts the energy technology assessment, which is informed by the tasks in phases 1 and 2. In addition, Phase 3 guides refining the scope of energy transition technology assessment, a final selection of the appropriate form of technology assessment and assessing the technology to achieve the overall purpose stipulated in Phase 1. In defining the purpose and scope, the focus is more on the technology within the broader sustainability implications, and the following questions are asked: What is the purpose of prioritised energy transition technology(ies)? What is the scope of analysis along the technology value chain? Who are the new stakeholders to include based on the redefined scope? Once the purpose and scope are refined, it is possible to select an appropriate assessment method based on the form chosen. Thus, the questions asked are: what form of technology assessment is appropriate? What will be the extent of stakeholder engagement beyond participation? The technology is thus assessed for the purpose, and the outcomes of the assessment can be communicated to influence public and policy debate, as well as technology design and development.

Similar to Phase 2, limited aspects of Phase 3 were incorporated into the South Africa case study. Thus, although the project is considered a technology assessment, it was more or less advancing the process of establishing buy-in to institutionalise energy technology assessment in South Africa rather than conducting assessments that produced outputs revealing policy implications of the prioritised technology from a sustainability perspective.

7. Conclusion

Advancing the practice and theory of energy technology assessment to support decision-making in energy transitions, encompassing SDG 7 and its interactions with other SDGs, is not a straightforward issue. Indeed, like all contemporary sustainability challenges, securing universal clean energy without disrupting existing systems is complex. Technology assessment has been practised since the 1970s, but gaps still exist about its framing and applications to manage energy transitions. The lack of formalisation of energy technology assessment also makes it challenging to effectively undertake assessment that informs energy transition decisions.

Therefore, this paper explored how technology assessment can contribute to advancing sustainable energy transitions in Africa. From the non-systematic integrative review, we synthesised ten unique forms of technology assessments. These are (i) classical technology assessment; (ii) participatory technology assessment; (iii) constructive technology assessment; (iv) real-time technology assessment; (v) indicative technology assessment; (vi) technology sustainability assessment; (vii) prospective technology assessment; (viii) interdisciplinary technology assessment; (ix) ethical technology assessment; (x) hermeneutic technology assessment.

We posit that most of the ten forms of technology assessments can be relevant to inform energy transition decision-making. However, since no single form of technology assessment can comprehensively assess all issues in the energy transition technology assessment, we developed an action-oriented energy technology assessment framework that builds upon the existing assessment approaches by considering the key process elements to advance each approach. Hence, an action-oriented technology assessment takes a transdisciplinary approach to promote sustainable energy transition, evaluate the sustainability of energy transition technologies in the context, and assess energy transition technologies within an energy system in the context. Further, we redefined energy technology assessment as *a deliberate endeavour to assess the potential and impacts of technological change [technology development] in an evolving energy system [dynamic system] to advance sustainability, design selection and utilisation of resources [sustainable development]*.

The study also proposed a 3-phased framework for implementing the action-oriented technology assessment. We used South Africa's case study pilot of green hydrogen technology assessment to explore the extent to which the project incorporated aspects of the proposed framework. Our study revealed that the existing energy transition technology assessments in Africa provide outputs that cannot inform decisions regarding sustainability and the policy implications of prioritised and assessed technology(ies). However, the UNCTAD pilot project was instrumental in initiating buy-in towards institutionalising technology assessment in African nations. In particular, UNCTAD methodology, which was mainly based on the parliamentary technology assessment practices in Europe, only encompassed the majority of Phase 1 aspects of our proposed framework. However, the order in which these must occur was improved in our proposed framework. A main limitation of the pilot project was that it followed a top-down process using UNCTAD's methodology developed from other contexts applied in Africa. This limited the extent of inclusive stakeholder engagement and relied on the steering committee and scientific experts.

Thus, we suggest that our proposed action-oriented energy technology assessment approach has three potential benefits. First, it has the potential to ensure that inclusive stakeholder engagement is central to energy technology assessment. Second, it can help articulate the scope for sustainable energy transition clearly to enable the initial choice of appropriate technology assessment forms. Finally, it can help ensure that assessments undertaken reveal and inform sustainability and policy implications of energy transition technology(ies).

Our study is not without limitations. Firstly, we utilised integrative review, taking a non-systematic approach to include peer reviewed and grey literature. While the approach provided a broad scope of documents to search, we likely did not include all the literature on the different forms of technology assessment. Secondly, although the study refers to examples of energy technology assessment in specific forms, we lack an in-depth discussion of the content of these examples. Future studies might undertake a focused, systematic review of the application of the different forms of technology assessment in the energy sector to expand their practice in energy transition decision-making. Further, due to the limited energy transition technology assessment projects in the African context, our study only used one of UNCTAD's pilot case studies. Despite these limitations, the South African case study enhanced our insights on the extent to which UNCTAD's project applied the aspects of the proposed 3-phased framework. Our future work will also entail applying and improving the 3-phased framework to more energy transition technology assessment projects in African case studies.

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