Towards an evidence base to support Power-to-X (PtX) decision-making in South Africa

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Summary Statement

Power-to-X (PtX) technology development is being rapidly pursued around the world. We present an initial evidence base to support strategic and site-specific decision-making for PtX in South Africa.

Abstract

Defossilisation is a priority, globally and in South Africa. Power-to-X (PtX) technologies could contribute greatly to achieving these ambitions. South Africa's renewable energy resources, land availability, platinum group metals resources, and port infrastructure, position it as a potential competitor in the global PtX economy. In addition to defossilisation, a domestic PtX economy could make substantial contributions to job creation, improve local livelihoods and facilitate a Just Energy Transition.

Vast technologies and infrastructure are required to create the electricity and water inputs to deliver PtX products (for domestic use and export), which, if developed at a sufficient speed, scale, and intensity, could have cumulative, unforeseen consequences. Given the complexity and sheer extent of the infrastructure required, a systems-thinking, data-driven, stepwise approach to site- and regional-scale decision-making is essential.

We present findings from a recent research study conducted by the Council for Scientific and Industrial Research (CSIR) for the German and South African governments, including:

- A detailed characterisation and description of South African PtX technology systems;
- A Driver-Pressure-State-Impact-Response (DPSIR) model integrating important social and environmental impacts and relationships;
- A spatial tool demonstrating regions most/least suitable for PtX development; and
- Site- and strategic-level recommendations to inform PtX decision-making.

Introduction

The transition from fossil fuels towards renewable energy is taking place globally, and in South Africa, at increasing pace and urgency. The global shift is driven by commitments to greenhouse gas reduction targets (IPCC, 2019) and the Sustainable Development Goals (SDGs) (Raman et al., 2022), plus the geopolitical need to develop new, sustainable energy supply chains and partnerships (Zakeri et al., 2022). Green hydrogen (GH_2) production and its Power-to-X (PtX) derivates (e.g. green ammonia and green methanol) may play a substantial, if not pivotal, role in this transition. PtX enables the conversion of electricity into high energy density carriers like hydrogen and synthetic fuels, which could replace fossil fuels in traditionally “hard-to-abate" sectors, like heavy-duty transport (e.g. shipping) and aviation.

South Africa’s renewable energy resources, extensive coastline, port infrastructure and platinum group metal reserves give it a competitive advantage in producing cost-effective PtX products (Lebrouhi et al., 2022). PtX could form a significant component of the South African energy economy over the next few decades if policy aspirations are realised. For this to happen, many decisions will need to be made at different spatial scales, across different spheres of government, involving a variety of stakeholders including the private sector and broader civil. Furthermore, if developed at sufficient speed, scale, and intensity, PtX development could have cumulative, unintended consequences. It is therefore prudent to openly embrace the prospects of a PtX economy in South Africa first by understanding the complex technological PtX system, recognising its potential benefits and risks, and thus pursuing holistic, co-produced, data-driven, and stepwise approaches to site and regional scale decision-making.

We present an initial evidence base to support PtX decision-making in South Africa using systems thinking approaches, Geographic Information Systems (GIS), as well as incorporating a mixed-method approach consisting of Working Group (WG) scoping workshops and quantitative surveys. The WG included representatives from various private and public organisations in engineering, sustainability science and policymaking.

Understanding the PtX technological system

Major infrastructure is required to enable PtX technologies (Lattemann & Höpner, 2008; Sheikh et al., 2016). The PtX technology system requires: electricity generated from renewable energies (RE) to power all components; freshwater – sustainably sourced from desalinated sea- or wastewater; electrolysers to produce GH_2; and facilities to synthesise ammonia or methanol by nitrogen and carbon inputs (Figure 1). This entire system further needs to be supported by various ancillary infrastructure like batteries, electricity transmission lines, pipelines, storage facilities, and roads to create a complete PtX value chain.

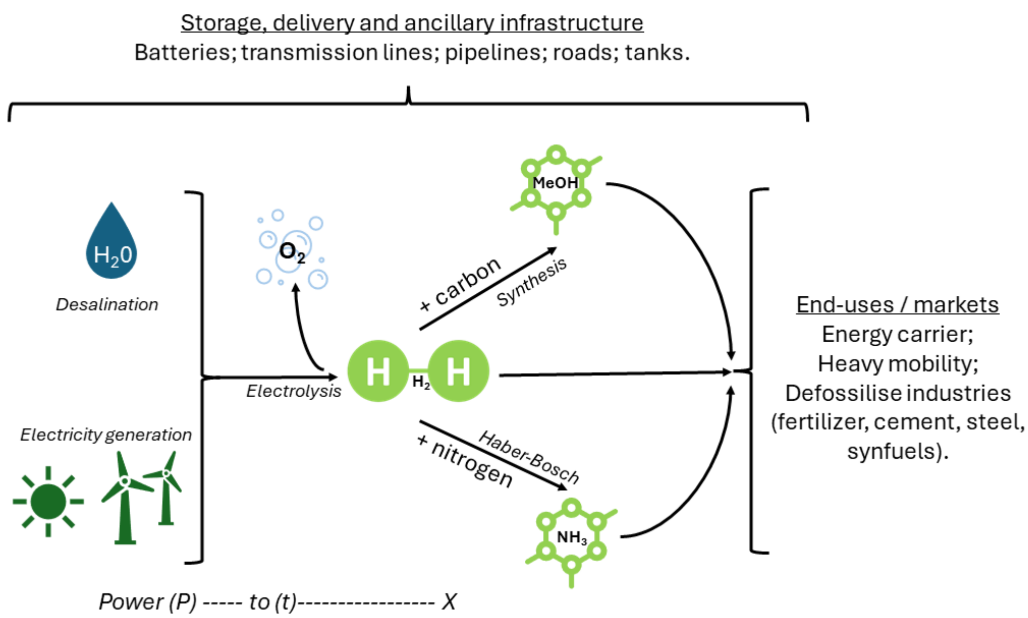


Figure 1: Electricity from renewable energy and sustainably-sourced water is used to produce hydrogen and a variety of PtX products including ammonia (NH_3) and methanol (MeOH), which have various end-uses.

Meeting the South African GH_2 production ambition of 4 Mt per annum (DTIC, 2022) would require new-build RE in the order of 40 GW, which translates into a land-take requirement in the order of 200 km^2 – only to power the elecrolyser component of the PtX technological system. This hints that land availability and conflict may well be a main constraint facing PtX development. Cumulative ecological and social footprints could rapidly approach or exceed limits of acceptable change and thus undermine progress towards SDGs. Quantitative assessment of PtX scenarios is needed to address uncertainties over the footprint scale required to support PtX production.

Contextualising potential benefits and risks

A Driver-Pressure-State-Impact-Response (DPSIR) causal framework (Cooper, 2013; OECD, 1993) was applied to present a high-level synopsis of the key environmental and social issues associated with a complex PtX technological system and economy (Figure 2).

Driving forces are the global and domestic trends pushing forward a South African PtX economy.

Pressures are the direct mechanisms through which PtX activities and infrastructure will positively and/or negatively affect people and the environment.

States are the most likely baseline receiving environments that will be affected by a South African PtX economy. They explain spatial aspect of the receiving environment and non-spatial aspects of the receiving environment.

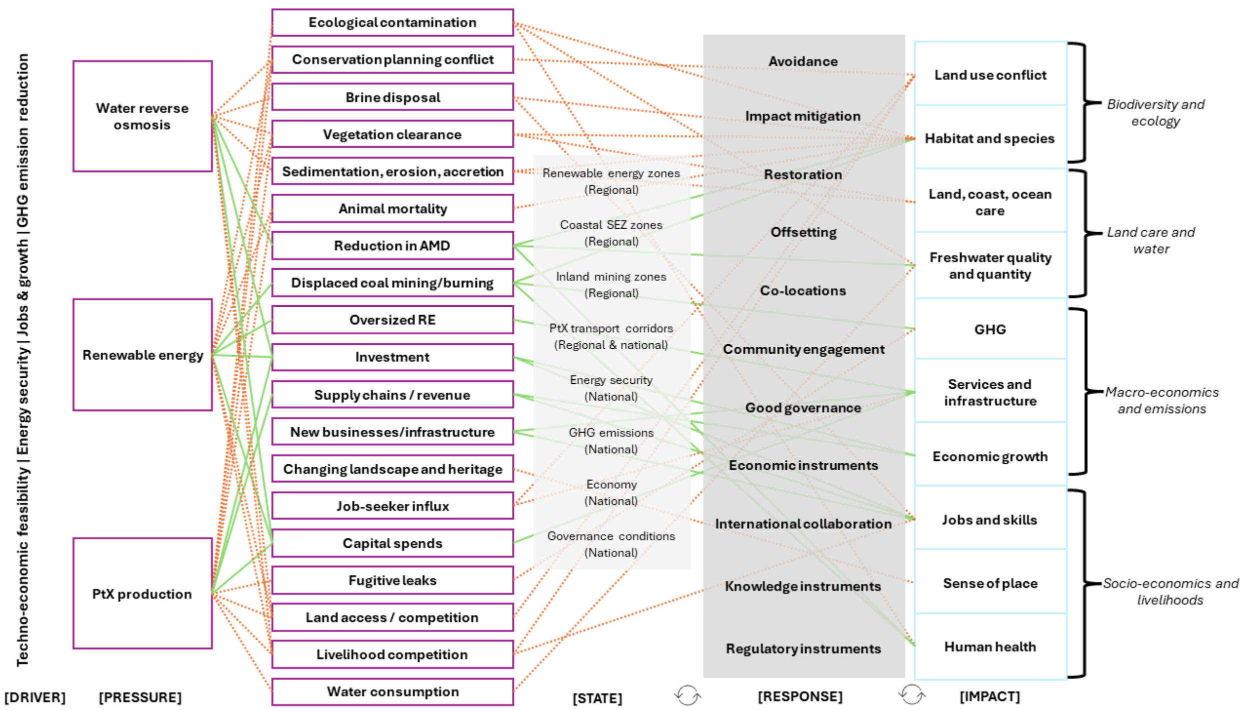
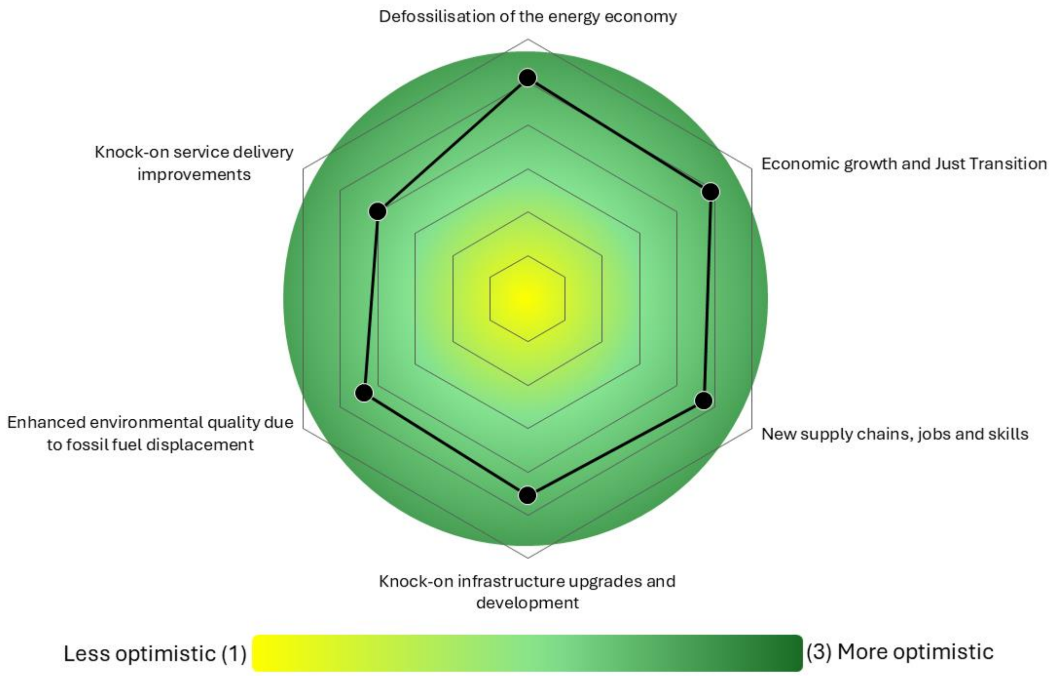


Figure 2: DPSIR summary diagram revealing a complex PtX social-ecological-technological system and the conceptual relationships between its drivers, pressures, states, impacts and responses. Responses can be implemented in anticipation of changing states to minimise adverse or maximise desirable impacts (as depicted here) or in reaction to changes that have manifested as impacts.

Responses are the options available for society to mitigate negative impacts and enhance positive ones. Eleven different responses classes were identified. Responses can be implemented in anticipation of changing states to minimise adverse or maximise desirable impacts or in reaction to changes that have manifested as impacts.

Impacts are net positive or negative effects on biophysical and social environments that may arise from PtX activities (Figure 3). Statements on these impacts were distributed to a multi-disciplinary WG (n=18). For positive impacts (green), WG members had to rate their levels of optimism, and for negative impacts (red), their levels of concern on a Likert Scale (1-3). Analysis of the WG responses provided an integrated, multidisciplinary perspective, highlighting which negative impacts posed the greatest risks, and which positive impacts may present the greatest opportunity.

a)



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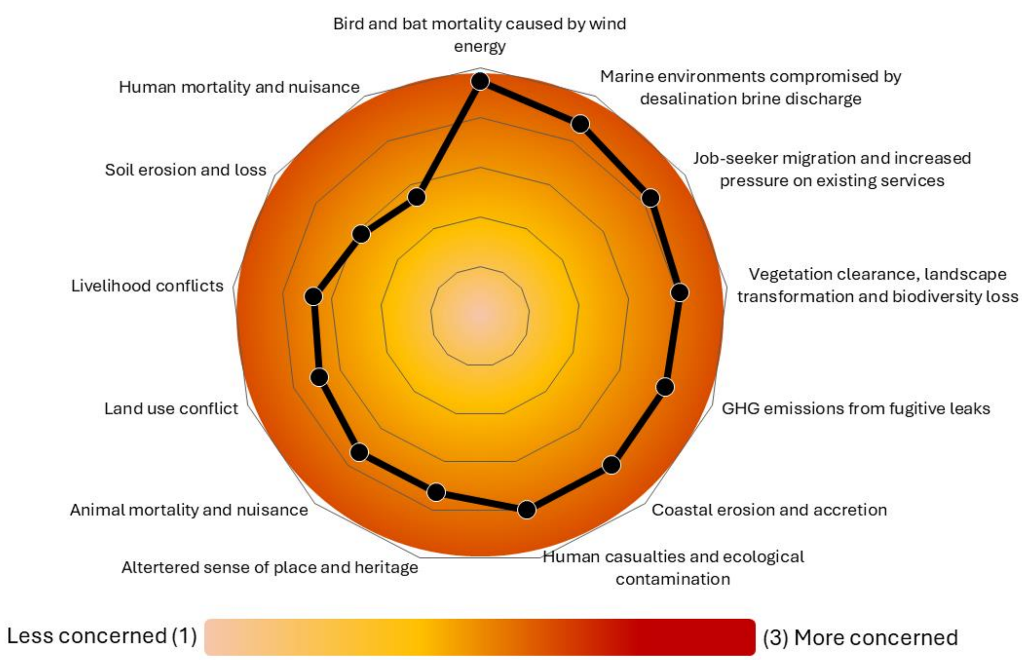


Figure 3: Outcome of co-produced scoping of PtX impacts where a Working Group (n=18) ranked their level of a) optimism for potential positive impacts; and b) concern about potential negative impacts.

Data driven decision-support

GIS analysis has increasingly become a crucial tool for sustainable infrastructure planning. It is used around the world for identifying suitable and optimal areas, based on a range of environmental, economic, and social parameters, for important infrastructure developments (DEA, 2015; Latinopoulos & Kechagia, 2015; Sánchez-Lozano et al., 2014), including more recently, for RE and GH_2 production (Messaoudi et al., 2019).

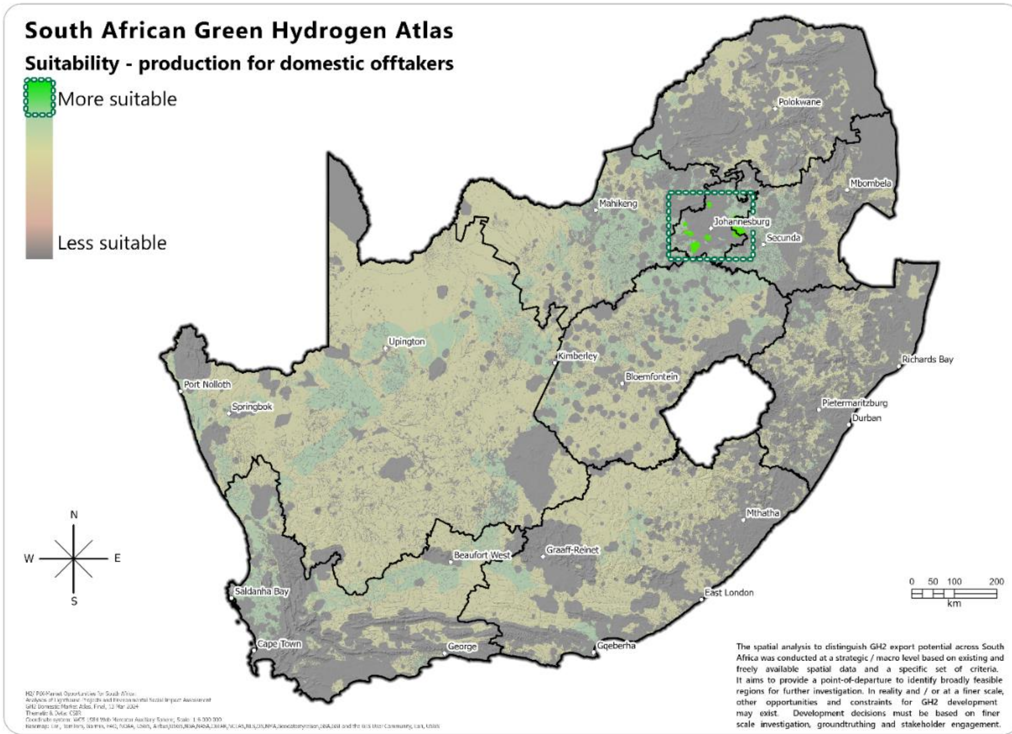
Spatially explicit siting variables which constituted ‘push’- or ‘pull’ factors included environmental conditions and sensitivities, political planning contexts, uses and users of the environment, and technical/engineering requirements (Table 1). Variables were assigned relative importance (weighted) with scores developed through interdisciplinary consultations within the WG.

Table 1: Variables considered in a spatial Multi-Criteria Analysis represented ‘push’ (< >) and ‘pull’ (> <) factors to determine suitable regions for PtX production in South Africa, considering both domestic and export markets, arranged from most to least important weighting.

<table>
<tr><th></th><th></th><th>Domestic Market</th><th>Export Market</th></tr>
<tr><td rowspan="21">Increasing relative importance →</td><td rowspan="3">Environmental safeguards (restricted)</td><td colspan="2">Protected Areas <></td></tr>
<tr><td colspan="2">Heritage features <></td></tr>
<tr><td colspan="2">Watercourses and wetlands <></td></tr>
<tr><td rowspan="3">Landuse and safety (restricted)</td><td colspan="2">Population density <></td></tr>
<tr><td colspan="2">Built-up areas (urban) <></td></tr>
<tr><td colspan="2">High-value agriculture <></td></tr>
<tr><td>Offtaker</td><td>Local industries (cement, steel, synfuel, oil) ><</td><td>Export ports ><</td></tr>
<tr><td>Renewable energy</td><td colspan="2">Solar & wind potential ><</td></tr>
<tr><td rowspan="3">Water</td><td colspan="2">Desalinated seawater ><</td></tr>
<tr><td>Acid mine drainage regions ><</td><td>-</td></tr>
<tr><td>Coal fired power stations ><</td><td>-</td></tr>
<tr><td>Enabling infrastructure</td><td colspan="2">Electricity grid ><</td></tr>
<tr><td rowspan="3">Environmental safeguards (non restricted)</td><td colspan="2">Important Bird Areas (wind) <></td></tr>
<tr><td colspan="2">Conservation Areas <></td></tr>
<tr><td colspan="2">Steep slopes <></td></tr>
<tr><td rowspan="2">Landuse and safety (non restricted)</td><td colspan="2">Other agriculture <></td></tr>
<tr><td colspan="2">Built-up areas (industrial) ><</td></tr>
<tr><td rowspan="2">Policy alignment</td><td>All Special Economic Zones (SEZs) ><</td><td>Export port SEZs ><</td></tr>
<tr><td colspan="2">Renewable Energy Development Zones (REDZ) >< and Electricity Grid Infrastructure (EGI) corridors ><</td></tr>
</table>

The resulting South African GH_2 Atlas is an aid to identify suitable regions for GH_2/PtX production, considering both export and domestic use options (Figure 4). Spatially explicit siting variables which constituted ‘push’- and/or ‘pull’-factors included environmental conditions and sensitivities, political planning contexts, uses and users of the environment, and technical/engineering requirements. Variables were weighted with scores developed through interdisciplinary consultations within the WG. The Atlas aims to provide a point-of-departure to identify broadly feasible regions for further investigation.

a)



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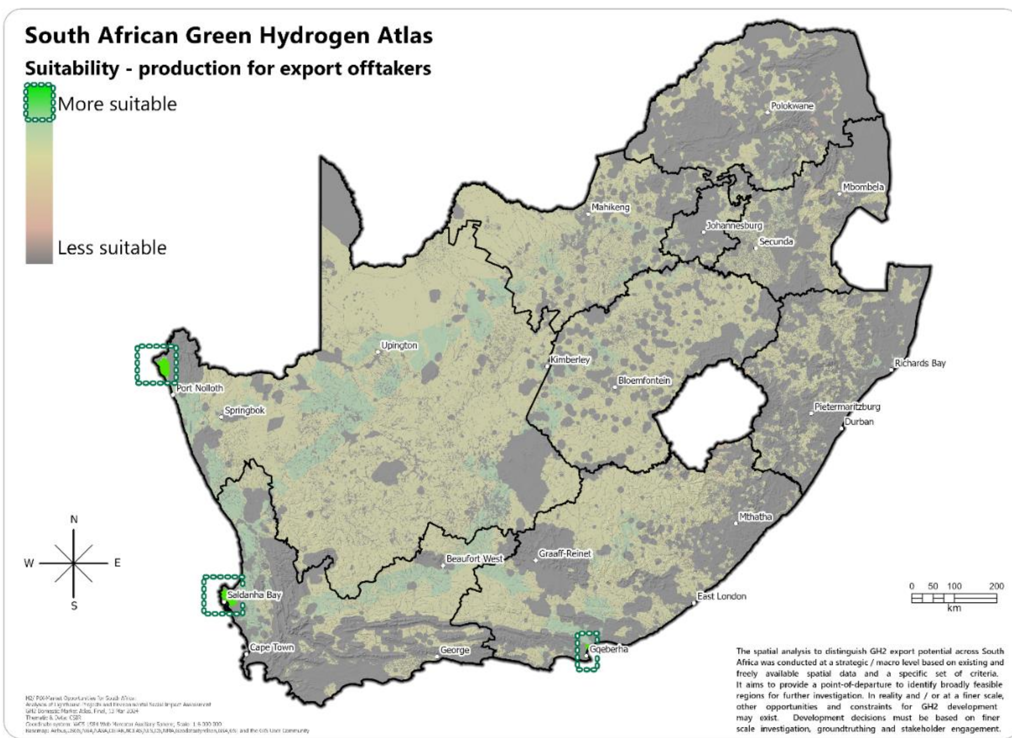

Figure 4: South African Green Hydrogen Atlas showing relative suitability for a) PtX production for domestic use; and b) PtX production for export.

Recommendations for PtX planning and decision-making

The scale and intensity of construction and operational activities required to support a burgeoning PtX economy need to be guided by wise, systems-based decision-making processes (USDOE, 2023) spanning all spheres of government and including the private sector and civil society, potentially over extended time periods. Most of these decisions will need to be contextual, meaning that certain activities may be permitted in one location and not others, or with a given set of requisite management actions. This will depend on the specific nature of the project proposal, its development activities, the local socio-economic context, and the ecological and cultural sensitivity of the location within which they are proposed, among other factors.

From an environmental and social sustainability perspective, the precautionary approach needs to be guided by robust processes of knowledge production, with the aim of promoting good decision-making. Two of the science-policy interfaces which are well established for this purpose are Strategic Environmental Assessment (SEA) for policy/programme-level guidance, and Environmental Impact Assessment (EIA), for project-level guidance.

SEA is a systematic decision support process aimed at ensuring that environmental and other sustainability aspects are considered effectively in policy, plan, and program making. In a broader sense, SEA seeks to integrate environmental and social considerations into strategic decision-making processes. To facilitate responsible and efficient decisions on PtX-related projects in the future at EIA-level, it is suggested that a strategic-level SEA is undertaken for PtX development in South Africa.

An SEA for PtX in South Africa should consider all development aspects and activities associated with a South African PtX economy, ranging from enabling infrastructure (e.g., renewable energy and seawater reverse osmosis), to competing land uses (e.g., tourism, conservation, and agriculture), to socio-economic issues of poverty, employment, human migration, social fabric and service infrastructure, as well as exploring the links with adjacent industries, provinces and countries also looking at PtX development.

Oriented by policy/programme-level knowledge production tools like SEA, site-specific good EIAs must be used to inform good decision-making for PtX project development, on a case-by-case basis. EIA tends to aggregate system elements into discrete ‘silos’ supporting administrative and bureaucratic efficiency (Bond et al., 2015). This is evident in the structure of an EIA report – usually separated amongst specialist studies. This makes it difficult to predict systemic effects, which can be several orders of magnitude more significant than direct impacts, (Lenzen et al., 2003). This may be particularly relevant when considering the complex technological PtX system, the components of which may sprawled over various and expansive geographies.

At the project level taking a systems perspective in conducting EIA from the outset, and employing certain tools that assist in gaining deeper insight into project impacts on complex receiving environments, can lead to more accurate and meaningful EIA outcomes. Such tools include cross-impact matrices, directed graphs, network analysis and scenario analysis, to mention a few (Duinker & Greig, 2007; European Commission, 1999; Perdicoúlis & Glasson, 2006). Despite the repeated acknowledgement that EIA and the decisions they inform would benefit from systems thinking approaches (Morrison-Saunders & Retief, 2012; Nooteboom, 2007), the uptake and application of these as common impact assessment practice has been slow. Mainstreaming systems thinking in EIA would require those commissioning and practising EIA to go beyond minimum requirements, an undertaking that could be constrained by available time, resources and systems thinking capabilities (Snyman-Van Der Walt et al., 2022).

Conclusion

Vast technologies and infrastructure are required to create the electricity and water inputs to deliver PtX products (for domestic use and export), which, if developed at a sufficient speed, scale, and intensity, could have cumulative, unintended consequences. Using systems thinking, co-produced knowledge and GIS analysis to initially contextualise the complex PtX technological system we present a foundational evidence base for future planning, assessment and decision-making on PtX projects towards the sustainable and responsible establishment of a South African PtX economy.

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