GREEN HYDROGEN
SOUTH AFRICA

H_2/PTX PROJECTS IN SOUTH AFRICA: A PRELIMINARY REVIEW OF THE ENVIRONMENTAL AND SOCIAL IMPACTS

Lighthouse H2/PtX Market Opportunities for South Africa

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Acronyms

AC	Alternating Current
AMD	Acid Mine Drainage
BESS	Battery Energy Storage Systems
CLD	Causal Loop Diagram
CO	Carbon Monoxide
CO_2	Carbon Dioxide
DC	Direct Current
DPSIR	Drivers-Pressures-States-Impacts-Responses
EAP	Environmental Assessment Practitioner
EIA	Environmental Impact Assessment
GDP	Gross Domestic Product
GHG	Greenhouse Gases
GIS	Geographic Information System
ha	Hectares
km	Kilometres
m	Metres
m^2	Square Metres
MLD	Million Litres Per Day
MW	Megawatts
Nm3	Normal Cubic Meters
O&M	Operations And Maintenance
PEM	Proton Exchange Membrane
PtX	Power-to-X
PV	Photovoltaics
REDZ	Renewable Energy Development Zone
RO	Reverse Osmosis
SAF	Sustainable Aviation Fuel
SEA	Strategic Environmental Assessment
SEZ	Special Economic Zone
SWRO	Seawater Reverse Osmosis
t	Tonnes
UV	Ultraviolet
WG	Working Group

Executive summary

Power-to-X (PtX) prospects in South Africa are driven by an increasing global demand, plus an urgent domestic need to end load-shedding and create a secure, diversified, decarbonised energy economy. The country's renewable energy resources, port infrastructure and platinum group metal reserves give it a competitive advantage in producing cost-effective PtX products. If these products were to form a considerable component of the South African energy economy over the next few decades, the macro socioeconomic benefits could be substantial. Likewise, the local benefits across the entire value chain of PtX production, storage, transportation (rail, pipelines, powerlines, roads, ports), and its potential end-uses, domestically and globally, could help to create new opportunities, jobs, and skills.

The technologies and infrastructure required to create the electricity and water inputs for the burgeoning South African PtX economy, such as wind turbines and solar PV panels, seawater, and mine water reverse osmosis plants (plus the thousands of kilometres of linear transport infrastructure), are major infrastructure developments, with a complex array of social and environmental impacts. If undesirable impacts are not properly avoided and mitigated in the project planning phases, individually or in accumulation, they could result in unacceptable social and environmental consequences.

Using the Drivers-Pressures-States-Impacts-Responses (DPSIR) causal framework and a series of Causal Loop Diagrams (CLDs), plus incorporating a mixed-method approach consisting of working group (WG) scoping workshops, literature reviews and a quantitative survey, this report:

1) Describes and characterises the most likely PtX technology sub-systems which may be developed if South Africa were to pursue a large-scale PtX economy.
2) Presents key environmental and social impacts which could emanate from the identified technology and infrastructure sub-systems.
3) Undertakes a preliminary assessment of the positive and negative impacts, ranking their importance or magnitude, and
4) Develops a set of policy/programme- and project-level- recommendations to inform decision-making on PtX programmes and projects going forward.

Given the extremely wide scope of the PtX technologies and infrastructure components, the lack of any concrete project or programme, or PtX development scenarios, this report offers a high-level (nonspecific) scoping of the environmental and social issues which may be associated with a South African PtX economy. The primary purpose of this report is to get a holistic sense of the environmental and social issues associated with a PtX economy, and to provide the technical basis which will support the development of a PtX Environmental Impact Assessment (EIA) guideline for South Africa.

The PtX technology sub-systems which will exert pressures onto several South African social and environmental receiving environments are:

- **Sub-system A:** Electricity via renewable energy – i) Onshore wind ii) Solar photovoltaics (PV)
- **Sub-system B:** Water via reverse osmosis (RO) – i) Seawater ii) Mine water
- **Sub-system C:** PtX Products – i) Hydrogen via electrolysis ii) Ammonia via Haber-Bosch iii) Methanol via synthesis
- **Sub-system D:** Transportation – Rail, roads, traffic, pipelines, ports, powerlines etc.

These technology sub-systems will cause pressures and impacts to manifest through diverse receiving environments, in different ways (Table 1).

Table 1: Issues raised by the WG were integrated into the DPSIR causal framework and calibrated with reviews of the peer reviewed and grey literature, to reveal the following relationships

DPSIR element	Description
Drivers *The global and domestic trends pushing forward a South African PtX economy.*	1. **Techno-economic feasibility** – Major advancements in renewable energy, reverse osmosis and PtX technologies. 2. **Need for energy security** – Global geopolitical risks and scarcity, plus national energy crisis. 3. **Need for jobs and growth** – Urgent national need to reduce poverty, unemployment, and inequality. 4. **Need to reduce Greenhouse Gas (GHG) emissions** – Global and national need to reduce GHG emissions.
Pressures *The direct mechanisms through which PtX activities and infrastructure that will affect people and the environment.*	1. **Financial investment** – Direct capital inflows from foreign or private sector investors. 2. **Land-use planning** – Regulatory decisions/policies guiding the nature and extent of PtX projects. 3. **Infrastructure construction** – Construction activities associated with initial project development. 4. **Operational activities** – Day-to-day operational activities associated with ongoing production. 5. **PtX transportation** – PtX logistics via rail, road, pipeline, port, and powerline.

DPSIR element	Description	
States *The most likely baseline receiving environments that will be affected by a South African PtX economy.*	1. Renewable Energy Development Zones (REDZs) (Regional) 2. Coastal Special Economic Zones (SEZs) (Regional) 3. Inland mining zones (Regional) 4. PtX transport corridors (Regional & national)	5. Energy security (National) 6. GHG emissions (National) 7. Economy (National) 8. Governance conditions (National)
Impacts *The net positive or negative effects on biophysical and social environments.*	1. Habitats and species 2. GHG emissions 3. Economic growth 4. Services and infrastructure 5. Land use conflicts	6. Jobs and skills 7. Human health 8. Sense of place 9. Water availability 10. Erosion/sediment movement
Responses *The options available for society to mitigate negative impacts and enhance positive ones.*	1. Avoidance 2. Impact mitigation 3. Restoration 4. Offsetting 5. Co-locations 6. Community engagement	7. Good governance 8. Economic instruments 9. International collaboration 10. Knowledge instruments 11. Regulatory instruments

From the DPSIR framework, and using a series of CLDs, positive (desirable) and negative (undesirable) impacts were identified and transposed into a survey, which was distributed to WG members for completion between 01 and 13 September 2023. The survey measured optimism (positive impacts) and concern (negative impacts) using a Likert Scale from 1-3, where 1 = not concerned/optimistic, 2 = concerned/optimistic, 3 = very concerned/optimistic (Table 2).

Table 2: Findings of the survey from 11 WG sustainability science practitioners, actively working on PtX projects, for both positive and negative impacts, with rank, mean (SD) and median responses for each survey statement

Survey statement	Rank	Mean	SD	Median
Renewable energy generation and use of green PtX products decarbonise South Africa's energy economy.	1	2.54	0.52	**Very optimistic**
Investment into PtX projects creates new revenues, markets, and supply chains, leading to economic growth and renewed confidence in the Just Transition.	2	2.45	0.52	**Optimistic**
Construction and operations of PtX projects create new businesses, supply chains, and jobs and skills for local people in the regions within which they occur.	3	2.36	0.81	**Very optimistic**
Turbine blades used at operational wind farms lead to bird and bat mortality.	4	2.36	0.67	**Concerned**
Capital spends on PtX-related transport (rail, roads, ports, pipelines, powerlines) create superior quality infrastructure at important transport networks and nodes e.g., national road connections…	5	2.27	0.65	**Optimistic**
Energy from PtX projects displace fossil fuels, improving the environmental quality of regions e.g., Mpumalanga, where coal mining, coal combustion, and acid mine drainage (AMD) are prevalent.	6	2.18	0.75	**Optimistic**
Brine from seawater reverse osmosis (SWRO) operations discharged to the marine environment causes a loss of habitats and species, affecting marine living resources and the people who depend on them.	7	2.18	0.75	**Concerned**
Job seeker and labourer in-migration during PtX project construction and operations place strain on already constrained municipalities, services, and infrastructure.	8	2.09	0.70	**Concerned**

Survey statement	Rank	Mean	SD	Median
Renewable energy construction and operations, and electricity transmission (powerlines) in rural, agricultural landscapes lead to vegetation clearance and the loss of habitats and species.	9	2.09	0.83	**Concerned**
SWRO construction and operations, and transport (pipelines) in coastal zones lead to vegetation clearance and the loss of habitats and species.	10	2.09	0.70	**Concerned**
Developing PtX projects and transport corridors (roads, rail, pipelines, powerlines) in regions that would otherwise be used for conservation leads to land-use conflict.	11	2.09	0.83	**Concerned**
Investment into PtX projects leads to better local infrastructure and services e.g., roads, water supply, wastewater treatment etc.	12	2	0.77	**Optimistic**
SWRO operational infrastructure alters coastal sediment movement regimes, causing coastline accretion and erosion.	13	2	0.77	**Concerned**
Explosions, leaks, and spills at PtX project operations, or during transport and handling, contribute toward human death or injury and ecological contamination.	14	2	0.63	**Concerned**
PtX project linear infrastructure construction (roads, rail, pipelines, powerlines) leads to vegetation clearance causing a loss of habitat and species.	15	1.91	0.83	**Concerned**
Renewable energy construction and operations, and electricity transmission (powerlines) in regions dependent economically on agricultural and tourism contribute to loss of local incomes.	16	1.9	0.94	**Concerned**
Renewable energy construction and operations, and electricity transmission (powerlines) in rural, agricultural landscapes lead to changes in aesthetics and heritage resources, causing loss of sense of place.	17	1.81	0.87	**Concerned**

Survey statement	Rank	Mean	SD	Median
Traffic, noise, dust, and physical collisions during PtX project construction, operations and transportation lead to losses of habitats and species e.g., animal roadkill.	18	1.81	0.75	Concerned
SWRO construction and operations, and transport (pipelines) within coastal environments lead to changes in aesthetics and heritage resources, causing an altered sense of place.	19	1.73	0.79	Concerned
Fugitive emissions, leaks, and purges from PtX project operations and transportation lead to increased GHG emissions.	20	1.72	0.79	Concerned
Use of scarce water resources during renewable energy construction and operations in rural, water-stressed regions leads to increased water scarcity.	21	1.72	0.79	Concerned
Authorising SWRO construction in coastal regions leads to constrained public access to the beach and coastal resources.	22	1.45	0.69	Not concerned
PtX project construction and operational activities (renewable energy, desalination, transport infrastructure) lead to soil instability and soil erosion.	23	1.45	0.69	Not concerned
PtX project construction and operations cause nuisance impacts to human health e.g., flicker, glare, noise, traffic, dust etc.	24	1.36	0.50	Not concerned
Authorising PtX projects and increasing competition within SEZs for prime property with port access leads to land use conflict.	25	1.36	0.67	Not concerned

1. Introduction

1.1 Background

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 GHG reduction targets (IPCC, 2019) and the Sustainable Development Goals (Raman et al., 2022), plus the geopolitical need to develop new, sustainable energy supply chains and partnerships (Zakeri et al., 2022). Power-to-X (PtX) technology may come to 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 and aviation. Advancements in renewable energy production and electrolyser efficiency (Ayodele and Munda, 2019; Shiva Kumar and Lim, 2022), mean that PtX offers a viable, affordable energy alternative (van Renssen, 2020).

The largest expected demand for South African-produced green hydrogen is export to the international market and sustainable bunker fuel for maritime vessels calling at South African ports (Saldanha Bay, Coega/Ngqura, Richard's Bay and Boegoebaai). The collective total demand and import targets for green hydrogen across the European Union, Germany, Japan, and South Korea is around 12 million tonnes (t) per annum by 2030. Conservative estimates indicate that South Africa's green hydrogen export potential is about 1.9 million tonnes per annum to 2050, corresponding to 7% of the global green hydrogen import market (DTIC, 2022). With respect to using PtX to augment South Africa's own energy security, the Super H$_2$igh Road Scenario report, commissioned by Agora Energiewende in June 2021, found that production of 3.8 million tonnes per annum of hydrogen could be developed in South Africa by 2050. If half that figure (~2 million tonnes per annum) were reserved for domestic consumption, it would contribute 8% of final energy demand in South Africa (IHS Markit, 2021).

Germany is one of the countries leading the development of a global PtX supply chain. The German National Hydrogen Strategy aims to advance the production, distribution, and use of hydrogen for Germany's energy transition and carbon reduction goals. The strategy offers financial support for hydrogen initiatives and encourages its adoption globally. The South African-German Cooperation has initiated several PtX projects in South Africa. PtX prospects in South Africa enjoy substantial support in the current political climate, evidenced by the publication of two seminal PtX policies: The Hydrogen Society Roadmap for South Africa (DSI, 2021) and the Green Hydrogen Commercialisation Strategy for South Africa (DTIC, 2022). This support is reflective of two essential needs.

Firstly, to end load-shedding, and create a secure, diversified energy infrastructure (Oliveira, Beswick and Yan, 2021). Secondly, to decarbonise the economy by creating sustainable economic growth, supporting a 'Just Transition'[1] away from coal (DSI, 2021).

The country's abundant renewable energy resources, port infrastructure and platinum group metal reserves, give it a competitive advantage in producing cost-effective PtX products for both domestic consumption and international export (Lebrouhi et al., 2022). Macro-socioeconomic benefits could include an improved trade balance, and increased foreign direct investment and Gross Domestic Product (GDP) (Fazioli and Pantaleone, 2021). Likewise, the local benefits across the entire value chain of PtX production, storage, transportation, and its potential end-uses, domestically and globally, could be substantial (IHS Markit, 2021). This is especially true for the renewable energy-rich rural regions of South Africa, where new investment could alleviate some of the social problems associated with endemic joblessness and poverty (Hamukoshi et al., 2022). Barriers that need to be overcome include electricity grid reliability and renewable energy availability, opaque standards, targets and strategies at the sector level, and lack of PtX transport and storage regulation. Possible enablers that need to be prioritised include financial support and incentives, streamlined permitting, carbon taxes, clear sector planning, and standardisation of technology and safety specifications (DSI, 2021).

The technologies and infrastructure required to create the electricity and water inputs for this potentially burgeoning economy [including wind turbines, solar PV panels and reverse osmosis (RO) desalination plants (seawater and contaminated mine water)], are major infrastructures (Lattemann and Höpner, 2008; Sheikh, Kocaoglu and Lutzenhiser, 2016). If developed at a sufficient speed, scale, and intensity, they could have cumulative, unforeseen consequences. With respect to the novel technologies of electrolysis, synthesis and Haber-Bosch, there currently exists very little research and monitoring data at industrial scale (Vallejos-Romero et al., 2023), making our current understanding mostly theoretical. It, therefore, would seem prudent to both openly embrace the prospects of a PtX economy in South Africa, acknowledging its explicit benefits when compared to the coal-based status quo, while at the same time remaining conscious of the unknowns, and committing to a systems-thinking, data-driven, stepwise approach to site and regional scale decision-making.

1 *The Just Transition is a policy framework for managing the shift from a high-carbon, environmentally degrading economy to a low-carbon, sustainable economy in a manner that is socially equitable and inclusive. South Africa, like many other countries, is faced with the challenge of reducing its greenhouse gas emissions while still addressing issues like poverty, unemployment, and social inequality.*

1.2 Purpose and structure

This project, as well as the H2.SA programme more generally, aims to improve the conditions for companies to participate in a South African PtX economy (Output 2) and enhance stakeholder knowledge of the potential environmental and social impacts associated such an economy (Output 4). Given the complexity and sheer extent of the infrastructure required to establish a new energy economy, it is well-known that systems-thinking is necessary to guide sustainable PtX production (USDOE, 2023).

Part of building an evidence base to support PtX decision-making includes improving our current understanding of important social and environmental impacts which may arise from a burgeoning South African PtX economy. For these reasons, this report includes the following objectives:

1. To describe and then characterise the PtX technology sub-systems, covering their key components, processes, and development activities.
2. To scope important environmental and social impacts which might result from the identified technology sub-systems and development activities using an integrated, systems-thinking approach.
3. To undertake a preliminary assessment of the identified positive and negative impacts, highlighting the positive impacts that promise the most opportunity and the negative impacts that pose the greatest risk.
4. To develop a set of site- and strategic-level recommendations to inform decision-making on PtX programmes and projects to mitigate negative impacts and enhance positive impacts.

The outputs from this study will be used as the substantive knowledge base for the development of an Environmental Impact Assessment (EIA) guideline for South Africa. The EIA guideline will synthesise essential EIA-related information for PtX project developers, Environmental Assessment Practitioners (EAPs), as well as South African policymakers and stakeholders.

1.3 Methods

1.3.1 Approach to knowledge coproduction

Public and private uptake of project deliverables is an essential element of overall project success. To ensure engagement with a diversity of stakeholders, the project team constituted a multidisciplinary WG, drawing in the views, experiences, and ideas of a broad spectrum of people and knowledges. The overarching purpose of the WG was to 1) act as a pool of experts with technical expertise and in-depth sectoral knowledge which could be drawn upon at certain intervals during the project and 2) enable the coproduction of content, ensuring quality, and to make sure that project deliverables are of benefit to a broad range of stakeholders and audiences.

The WG had a deliberative content production function but was not a mandated decision-making and/or consensus seeking group. All positions in the WG were non-remunerate roles, with the ultimate benefit of participation derived from members having the opportunity to learn more about a potential PtX economy in South Africa, as well as the opportunity to coproduce important project outputs, with the added advantage of being officially cited ad hominem, as well as members of their respective organizations.

Table 3: Working group members, their organisations and respective knowledge domains (categorised as either 1) policymaking, 2) sustainability sciences or 3) engineering)

Name	Organisation	Knowledge domain
Amanda Makgoga	Transnet TNPA	Engineering
Aradhna Pandarum	CSIR	Engineering
Ashlea Strong	WSP	Sustainability sciences
Barry Clark	Anchor Environmental	Sustainability sciences
Bhavra Deonarain	NBI	Sustainability sciences
Dawid Bosman	TCTA	Engineering
Declan Morkel	SAWEA	Engineering
Dmitri Bessarabov	North-West University	Engineering
Federico Villatico	GFA	Engineering
Geeta Morar	NBI	Sustainability sciences
Gerhard Fourie	DTIC	Policymaking
Godrej Rustomjee	The African Climate Foundation	Sustainability sciences
Greg Schreiner	CSIR	Sustainability sciences
Henrik Uehlecke	GFA	Engineering
Jacqui Fincham	WSP	Sustainability sciences

Name	Organisation	Knowledge domain
James Mpofu	Transnet TNPA	Engineering
Jenitha Badul	DFFE	Policymaking
Jongikhaya Witi	DFFE	Policymaking
Lee Ann Richards	DFFE	Policymaking
Lelani Claassen	Cabanga Environmental	Sustainability sciences
Luanita Snyman-van der Walt	CSIR	Sustainability sciences
Magenthran Ruthenavelu	Transnet TNPA	Engineering
Mahandra Rooplal	IDC	Engineering
Mthunzi Mangqalaza	DMRE	Policymaking
Niveshen Govender	SAWEA	Sustainability sciences
Nomawethu Qase	DMRE	Policymaking
Oratiloe Sathekge	SAWEA	Sustainability sciences
Phillimon Modisha	North-West University	Engineering
Pulane Manale	DoT	Policymaking
Rethabile Melamu	SAPVIA	Sustainability sciences
Ronald Marais	ESKOM	Engineering
Rudolph Retief	Impact Water Solutions	Sustainability sciences
Saliem Fakir	The African Climate Foundation	Sustainability sciences
Santosh Sookgrim	SAWEA	Engineering
Stuart Heather-Clark	SLR	Sustainability sciences
Tauqeer Ahmed	Transnet TNPA	Engineering
Theoneste Uhorakeye	GFA	Engineering
Thomas Roos	CSIR	Engineering
William Stafford	CSIR	Sustainability sciences

1.3.2 Impact identification

The production of PtX products at scale is a diverse and multifaceted process, with many direct and indirect impacts, requiring an integrated, systems-based approach to design and decision-making (USDOE, 2023). For this reason, in collaboration with the WG, we crafted a schematic model of the different technology sub-systems and resource inputs and outputs (Figure 1). From the relevant literature, we described, in as much detail as possible, the types of development activities which may be associated with each of the technology sub-systems. We hosted a scoping session with the WG, drawing upon their diverse expertise, to identify the potential social and environmental issues associated with the development activities. We synthesised the outputs of this scoping exercise with the results of a literature review, covering peer reviewed journal publications and scoping/EIA reports for renewable energy, reverse osmosis, and/or any other relevant publications covering the impacts associated with PtX production.

1.3.2.1 DPSIR causal framework

We used a DPSIR causal framework to integrate the identified issues. DPSIR was developed by the European Environment Agency and has been widely used in environmental management and policymaking to analyse the complex cause-and-effect relationships that exist in human-environment systems. DPSIR offers a systematic way of identifying and understanding cause-and-effect relationships more clearly, providing a framework to analyse issues and inform policymakers about where interventions might be most effective. All DPSIR system elements were visualised using CLDs. CLDs are a graphical tool used to visualise and understand the interrelated variables within a complex system. They help to identify how different elements within a system are interconnected and influence each other over time.

1.3.1 Impact assessment

Drawing from the WG and the literature, using the DPSIR framework, pressure-impact relationships were identified, representing both positive (desirable) and negative (undesirable) impacts. These impacts were subsequently transcribed into an online survey and slated for dissemination amongst WG members. The survey was designed in such a way that for each negative impact, respondents were required to express their level of concern. They chose from three gradations: 'Very concerned', 'Concerned', or 'Not concerned'. Conversely, for positive impacts, respondents were prompted to convey their level of optimism, with choices spanning 'Very optimistic', 'Optimistic', or 'Not optimistic'. Analysis of the WG responses provided an integrated, multidisciplinary perspective, highlighting which negative impacts posed the greatest risks, and which positive impacts promised the greatest opportunity.

1.4 Scope

The scope the environmental and social impacts covered were drawn from the technology sub-systems shown in Figure 1. These sub-systems are the development and operational mechanisms which exert a direct pressure on the South African social and biophysical environment. The technology system included in the study comprises the following sub-systems:

- Sub-system A: Electricity via renewable energy – i) Onshore wind ii) Solar PV
- Sub-system B: Water via RO – i) Seawater ii) Mine water
- Sub-system C: PtX products – i) Hydrogen via electrolysis ii) Ammonia via Haber-Bosch iii) Methanol via synthesis
- Sub-system D: Transportation – (rail, roads, trucks, pipelines, ports, powerlines)

Given the extremely wide scope of the PtX technologies and infrastructure components, the lack of any concrete project or programme, or PtX development scenarios, this report offers a high-level (nonspecific) synopsis of the environmental and social issue that may be associated with a South African PtX economy. The report provides the technical basis which will support the development of an EIA guideline for South Africa, aimed at EAPs, case officers and project developers.

The report does not cover in any detail the downstream, life-cycle impacts associated with a PtX economy such as those associated with use of products like fertilizers and synthetic fuels.

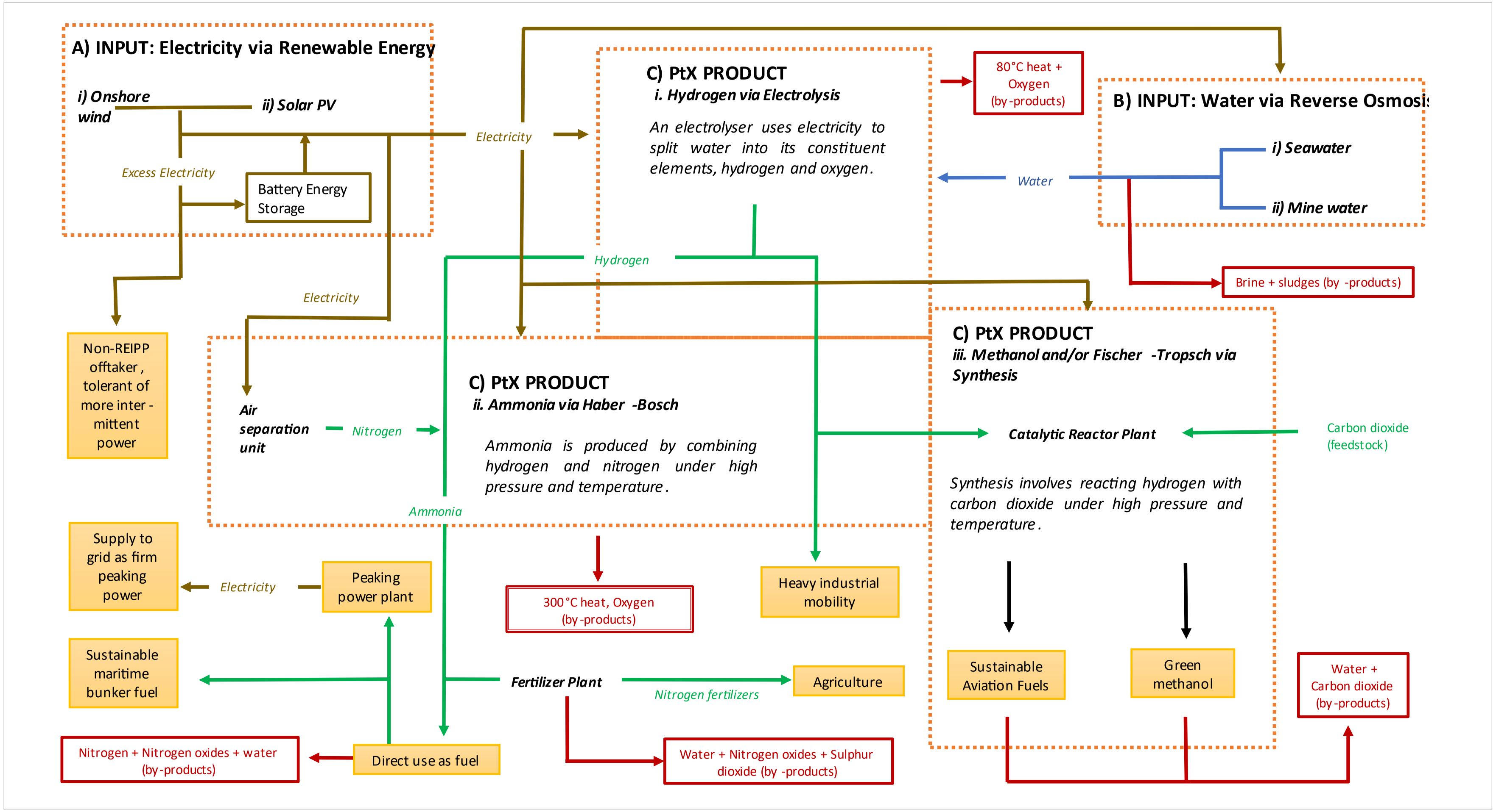

Figure 1: System inputs include sub-system A [electricity via renewable energy] and sub-system B [water via reverse osmosis] to produce the PtX products in sub-system C [hydrogen via electrolysis, ammonia via Haber-Bosch, and methanol via synthesis]. PtX products would be stored onsite, then transported via road, rail, and pipeline, to urban centres for domestic use and/or to South African ports for export. The expected domestic end-uses are shown in the cream boxes. Red boxes indicate by-products.

2. Subsystem A: Electricity via renewable energy

Each of the technology sub-systems in Figure 1 will be described in the sections that follow in terms of their key project components and development activities.

2.1 Wind

Wind energy harnesses the power of the wind to generate electricity. Wind turbines, comprising large blades mounted on a tower, capture the kinetic energy of the wind. As the wind blows, it spins the blades, which in turn drive a generator inside the turbine's nacelle to produce electricity.

2.1.1 Project components

i **Wind turbines:** The wind turbines are the primary components, consisting of a rotor with multiple blades, a nacelle housing the generator and gearbox, and a tower supporting the entire structure. Modern wind turbines are of various sizes and capacities, typically ranging from 4 megawatts (MW) to 8 MW or more per unit. Assumed hub height is in the region of 150-180 metres (m), while blade lengths are ~100 m (CSIR, 2023).

ii. **Foundations:** Wind turbine foundations are designed to support the turbine towers and withstand the forces generated during operation. There are different types of foundations, such as gravity-based, pile-supported, or rock-anchored foundations, depending on the soil conditions and turbine size. Assume foundation size in the region of 32 square metres (m^2) (CSIR, 2023).

Box 1: The Khobab and Loeriesfontein 2 wind farm

The Khobab and Loeriesfontein 2 wind farm is located in the Northern Cape province of South Africa and has a generating capacity of 283 MW, making it the largest wind farm in South Africa. This wind farm consists of 122 wind turbines, each of which is a Siemens SWT-2.3-108 turbine with a capacity of 2.3 MW. The turbines are in an area with strong winds, which allows them to generate electricity efficiently. The wind farm is connected to the national electricity grid, allowing the electricity to be distributed to consumers. The construction and operation of the wind farm has created jobs and economic opportunities in the local community.

Image: https://fairwind.com/project/khobab-loeriesfontein/

iii. **Access and internal service roads:** A network of access roads would be constructed to facilitate transportation of heavy equipment and materials during the construction phase, and for ongoing maintenance and inspection throughout the operational life of the wind farm.

iv. **Battery energy storage systems (BESS):** The BESS will store excess electricity generated from renewable sources during periods of low demand. BESS comprises a series of interconnected lithium-ion or flow batteries, inverters, and control systems. The stored energy can be dispatched during periods of high demand or low renewable generation, ensuring a stable and reliable electricity supply for the electrolysis process.

v. **Electrical collection system:** The electrical collection system includes an array of underground or overhead cables connecting the wind turbines to a central collection point or substation. This system collects the electricity generated by each turbine and transmits it to the substation for further processing.

vi. **Substation:** The substation is responsible for stepping up the voltage of the electricity generated by the wind turbines to match the voltage of the transmission grid. It contains transformers, switchgear, protection devices, and metering equipment. Can be anywhere from 2-6 hectares (ha) in footprint, with a built infrastructure height of around 10 m (CSIR, 2023).

vii. **Transmission lines:** High-voltage transmission lines connect the wind farm substation to the electrical grid, facilitating the export of the generated electricity to consumers.

v.iii **Temporary construction camp and laydown areas:** Facilities to house construction machinery and materials over the duration of the construction phase.

ix. **Operations and maintenance (O&M):** O&M facilities of about 2-4 ha in size (CSIR, 2023) are established to support the ongoing operation, maintenance, and repair of the wind farm. These facilities may include an office, storage, and workshop areas, as well as equipment and vehicles necessary for maintaining the wind turbines and associated infrastructure.

x. **Meteorological towers:** Meteorological towers are installed to monitor wind speed, direction, and other weather parameters, providing essential data for optimizing wind farm performance and maintenance planning.

2.1.2 Development activities

i. **Wind turbines:** a. Site preparation, including clearing and levelling. b. Transporting turbine components (blades, nacelle, tower sections) to site. c. Assembling the rotor, nacelle, and tower sections on the ground. d. Erecting the tower using cranes and lifting equipment. e. Installing the nacelle and rotor assembly atop the tower.

ii. **Foundations:** a. Performing geotechnical surveys to evaluate soil conditions. b. Excavating the site to the appropriate depth. c. Installing reinforcement bars or other structural support materials. d. Pouring the concrete and allowing it to cure. e. Finishing and inspecting the foundation before turbine installation.

iii. **Access and internal service roads:** a. Site survey and planning for the most efficient road network. b. Clearing and grading the land for road construction. c. Installing necessary drainage and erosion controls. d. Laying down the road base and compacting it. e. Applying the final road surface, typically gravel or asphalt. f. Marking roads and installing signage for safety.

iv. **BESS:** a. Determining the optimal location for the BESS. b. Preparing the site, including any necessary excavation. c. Installing the battery modules, inverters, and control systems. d. Connecting the BESS to the electrical collection system. e. Testing and commissioning the BESS.

v. **Electrical collection system:** a. Planning and designing the layout of the collection system. b. Trenching or drilling for the installation of underground cables, or erecting poles for overhead cables. c. Laying and securing cables. d. Connecting cables to each turbine and to the substation. e. Testing the system for proper operation.

vi. **Substation:** a. Choosing a location and preparing the site. b. Constructing the substation infrastructure including transformers, switchgear, protection devices, and metering equipment. c. Connecting the substation to the electrical collection system and the transmission grid. d. Testing and commissioning the substation.

vii. **Transmission lines:** a. Designing the route and securing necessary rights-of-way. b. Installing transmission towers or poles. c. Stringing and tensioning the transmission lines. d. Connecting the lines to the substation and the grid. e. Testing the lines to ensure proper operation and safety.

vii. **Temporary construction camp and laydown areas:** a. Selecting suitable locations and preparing the sites. b. Setting up temporary buildings, storage areas, and utilities. c. Ensuring compliance with safety and environmental regulations. d. Dismantling and restoring the area after completion of construction.

ix. **O&M:** a. Designing and preparing the site for the O&M facilities. b. Constructing buildings, storage, and workshop areas. c. Procuring necessary equipment and vehicles. d. Hiring and training maintenance staff.

x. **Meteorological towers:** a. Selecting appropriate locations based on wind resource assessment. b. Preparing the sites and erecting the towers. c. Installing meteorological instruments. d. Connecting the towers to the data collection and monitoring system. e. Regular calibration and maintenance of the instruments.

2.2 Solar PV

Solar PV installations consist of large-scale ground-mounted or rooftop solar arrays. The arrays comprise photovoltaic modules with monocrystalline or polycrystalline silicon cells, which convert sunlight into electricity. The generated electricity is transmitted to a central inverter where the direct current (DC) is converted to alternating current (AC) and then directed to the grid or the electrolyser facility.

2.2.1 Project components

i. **Solar panels:** Solar panels, also known as PV modules, are devices designed to capture and convert sunlight into electrical energy. They consist of numerous individual solar cells made from semiconductor materials like silicon. These would be mounted in arrays at a height of ~6 m (CSIR, 2022).

ii. **Inverters:** Inverters convert the DC electricity generated by solar panels into AC electricity.

iii. **Tracking systems:** Advanced tracking systems ensure optimal orientation of solar panels towards the sun, maximizing energy capture (CSIR, 2022). PV panel structure could include the following possible tracking and mounting systems):

   a. Single axis tracking structures (aligned north-south)

   b. Fixed axis tracking (aligned east-west)

   c. Dual axis tracking (aligned east-west and north-south)

   d. Fixed tilt mounting structure

   e. Bifacial solar modules

iv. **Mounting structures:** Robust mounting structures provide support and stability for solar panels, ensuring longevity and resistance to environmental factors.

v. **BESS:** The BESS will store excess electricity generated from renewable sources during periods of low demand. BESS comprises a series of interconnected lithium-ion or flow batteries, inverters, and control systems. The stored energy can be dispatched during periods of high demand or low renewable generation, ensuring a stable and reliable electricity supply for the electrolysis process.

vi. **Foundations:** Well-designed foundations support mounting structures, ensuring the stability and durability of solar panels and other system components.

vii. **Access and internal service roads:** Proper access roads are built throughout the solar farm, facilitating transportation, maintenance, and emergency access.

viii. **Electrical collection system:** Strategically placed electrical collection stations aggregate power from multiple solar arrays before sending it to substations or the grid.

ix. **Substations:** Substations receive the generated electricity, transforming voltage levels as needed and ensuring proper grid integration.

x. **Transmission lines:** Transmission lines transport the electricity generated by the solar PV system from substations to the grid or other points of consumption, such as the electrolysis facility.

xi. **Electrical components:** Wiring, combiner boxes, and other electrical components interconnect solar panels, inverters, and other system components, allowing efficient transmission and distribution of generated electricity.

xii. **Control and monitoring system:** A centralized control and monitoring system ensures efficient operation and maintenance, providing real-time performance data and enabling early detection of potential issues.

xiii. **O&M:** O&M facilities are established to support the ongoing operation, maintenance, and repair of the wind farm. These facilities may include an office, storage, and workshop areas, as well as equipment and vehicles necessary for maintaining the wind turbines and associated infrastructure.

Box 2: Solar Capital De Aar Project

The De Aar Solar Power farm is a large-scale solar PV power plant located in the Northern Cape province. It has a generating capacity of 175 MW, making it the largest solar farm in South Africa and Sub-Saharan Africa. It consists of over half a million solar panels, spread over an area of 473 ha. The panels are mounted on single-axis trackers, which allow them to track the sun throughout the day and generate electricity more efficiently. The solar farm demonstrates that large-scale solar power plants are technically feasible and can be a significant contributor to the country's energy mix.

Image: https://mybroadband.co.za/news/energy/476185-biggest-solar-plant-in-south-africa-vs-the-world.html

2.2.2 Development activities

i. **Solar panels:** a. Site preparation and grading for solar panel installation. b. Installation of solar panels and securing to mounting structures.

ii. **Inverters:** a. Installation of inverters and interconnection with solar panel arrays. b. Connection to electrical collection systems and BESS.

iii. **Tracking systems:** a. Assembly and installation of tracking systems on mounting structures. b. Calibration and testing to ensure optimal orientation and performance.

iv. **Mounting structures:** a. Construction and installation of mounting structure foundations. b. Assembly and erection of mounting structures.

v. **BESS:** a. Site preparation and grading for BESS installation. b. Installation of battery modules, inverters, and control systems. c. Connection to solar PV system and electrical grid.

vi. **Foundations:** a. Excavation and preparation of foundation sites. b. Installation of foundation materials and reinforcements. c. Pouring and curing of concrete.

vii. **Access roads:** a. Site surveying and design of access road network. b. Clearing and grading of land for road construction. c. Installation of drainage systems and erosion control measures. d. Construction of road base, surfacing, and final grading.

viii. **Electrical collection system:** a. Installation of electrical collection stations and transformers. b. Trenching and installation of underground cables or overhead lines to connect solar arrays to the collection system.

ix. **Substations:** a. Site preparation and grading for substation construction. b. Installation of transformers, switchgear, and other substation equipment. c. Connection to electrical collection system and transmission lines.

x. **Transmission lines:** a. Construction of transmission line corridors. b. Increased risk of bird collisions with transmission lines. c. Transmission towers and cables.

xi. **Electrical components:** a. Installation of wiring and combiner boxes for solar panel interconnection. b. Trenching and installation of underground cables or overhead lines to connect system components.

xii. **Control and monitoring system:** a. Installation of monitoring equipment, such as sensors, meters, and control devices. b. Setup and configuration of the centralized control system for real-time monitoring and data analysis.

xiii. **O&M:** a. Construction of O&M facilities, including offices, storage, and workshops. b. Procurement and setup of equipment and vehicles for maintenance activities. c. Training and onboarding of O&M personnel for efficient operation and maintenance of the solar PV system.

3. Subsystem B: Hydrogen via electrolysis

Hydrogen production occurs through water electrolysis, using electricity from wind and solar PV. The electrolyser facility consists of an array of polymer electrolyte membranes or alkaline electrolysers, which separate water into hydrogen and oxygen. The produced hydrogen is then compressed, stored in high-pressure storage tanks or underground caverns, and distributed to the ammonia and methanol production facilities or for other applications.

3.1 Project components

i. **Electrolyser:** The electrolyser is the core component of the system, where water is split into hydrogen and oxygen using an electrical current. There are three main types of electrolysers: alkaline electrolysers, proton exchange membrane (PEM) electrolysers, and solid oxide electrolysers. Assume footprint of 1-3 ha (WSP, 2022).

ii. **Power supply:** The power supply provides the necessary electrical energy for the electrolysis process. This can be sourced from renewable energy sources, such as solar PV or wind turbines, to produce green hydrogen.

iii. **Water purification unit:** A water purification unit, typically using reverse osmosis or other filtration methods, provides the high-purity water required for the electrolysis process to minimize the risk of contamination and ensure efficient operation. Assume approximate footprint of 1.5 ha (WSP, 2022).

iv. **Gas separation and compression:** After electrolysis, the produced hydrogen and oxygen gases are separated and compressed for

Box 3: The Fukushima Hydrogen Research Field (FH2R) project

The FH2R project uses a 20 MW solar PV array to power a single-stack 10 MW-class electrolyser. The electrolyser uses water to produce green hydrogen, which is then stored and supplied to users. The hydrogen production capacity of the project is up to 1,200 normal cubic meters (Nm3) of hydrogen per hour. Green hydrogen can then be converted into other energy carriers, like ammonia and methanol.

Image: https://www.power-eng.com/emissions/japanese-launch-worlds-largest-class-hydrogen-production-unit/

storage or transportation. Compression is typically achieved using compressors or pumps designed for high-pressure hydrogen applications.

v. **Hydrogen storage:** Hydrogen storage solutions can include high-pressure gas cylinders, underground storage, or liquid hydrogen storage through cryogenic cooling. The choice of storage method depends on the application, capacity, and specific project requirements.

Vi. **Control and monitoring system:** A control and monitoring system manages the operation of the electrolyser, ensuring optimal performance, and monitors key parameters such as temperature, pressure, and flow rates. It also provides diagnostic information for maintenance and troubleshooting.

vii. **Heat management system:** The electrolysis process generates heat, which must be managed to maintain optimal operating temperatures. A heat management system, typically using heat exchangers and cooling loops, helps to dissipate excess heat, and maintain the electrolyser at the desired temperature.

vii. **Safety systems:** Safety systems, including pressure relief valves, gas detectors, and emergency shutdown systems, are essential for ensuring safe operation and mitigating potential hazards associated with hydrogen production and handling.

ix. **Balance of plant:** The balance of the plant includes auxiliary components and infrastructure necessary to support the electrolysis process, such as piping, electrical connections, mechanical, fencing etc. (WSP, 2022).

3.2 Development activities

i. **Electrolyser:** a. Assembly and installation of the electrolyser unit. b. Integration with power supply, water purification unit, and gas separation systems.

ii. **Power supply:** a. Installation of electrical connections between the power source (e.g., solar PV or wind turbines) and the electrolyser. b. Setup of control systems to manage and optimize power usage.

iii. **Water purification unit:** a. Installation of reverse osmosis or other filtration systems. b. Connection to the electrolyser and integration with water supply infrastructure.

iv. **Gas separation and compression:** a. Installation of gas separation equipment, such as membranes or separators. b. Installation and connection of compressors or pumps for hydrogen and oxygen compression.

v. **Hydrogen storage:** a. Construction of hydrogen storage facilities, which may include high-pressure gas cylinders, underground storage, or cryogenic tanks. b. Connection to the gas separation and compression system for efficient hydrogen transfer.

vi. **Control and monitoring system:** a. Installation of control devices, sensors, and monitoring equipment. b. Setup and configuration of the centralized control system for real-time monitoring and data analysis.

vii. **Heat management system:** a. Installation of heat exchangers, cooling loops, and associated equipment. b. Integration with the electrolyser and control system to maintain optimal operating temperatures.

viii. **Safety systems:** a. Installation of pressure relief valves, gas detectors, and emergency shutdown systems. b. Testing and calibration of safety systems to ensure proper functionality and responsiveness.

ix. **Balance of plant:** a. Installation of auxiliary components, such as piping, electrical connections, and mechanical supports. b. Integration with the electrolyser and other systems to provide a cohesive and efficient hydrogen production facility.

4. Subsystem C: Water via reverse osmosis

This section describes the projects components and development activities associate with large-scale seawater reverse osmosis and mine wastewater reverse osmosis.

4.1 Seawater reverse osmosis

Seawater reverse osmosis (SWRO) is employed to provide a reliable source of freshwater for electrolysis and other processes. The seawater RO system consists of pre-treatment facilities to remove suspended solids, dissolved gases, and other impurities, followed by high-pressure pumps and RO membranes. The treated water is then stored in dedicated tanks and distributed to the electrolyser facility (CSIR, 2020).

4.1.1 Project components

i. **Marine intake:** A system designed to collect seawater from the ocean, which includes intake structures, screening systems, and pumps to transport water to the pre-treatment stage (CSIR, 2020).

ii. **Marine outfall:** Pipelines responsible for carrying the concentrated brine by-product away from the plant to the designated discharge location, where it is diluted and dispersed to minimize environmental impacts.

iii. **Pre-treatment:** A series of processes, such as coagulation, flocculation, sedimentation, and filtration, that remove particulates, organic matter, and other impurities from seawater to protect the reverse osmosis membranes from fouling.

iv. **Plant facility:** The main facility housing multiple parallel reverse osmosis trains, each consisting of high-pressure pumps, energy

Box 4: Adelaide seawater desalination plant

The Adelaide seawater desalination plant in South Australia has a capacity of 300 million litres per day (MLD), making it the largest desalination plant in Australia. Reverse osmosis technology is used to desalinate seawater and the plant covers approximately 20 ha, equivalent to about 50 football fields. The plant has a number of large infrastructure components, including seawater intake systems, a brine outfall system, and a water treatment system.

Image: https://www.abc.net.au/news/2019-11-07/how-will-the-sa-desal-plant-revival-help-australian-farmers/11682044 recovery devices, and RO membrane modules, designed for efficient and scalable production of fresh water. High-pressure pumps force seawater through semi-permeable membranes that separate dissolved salts, minerals, and other contaminants from the water, producing fresh, potable water. Assume 5-10 ha footprint (CSIR, 2020).

v. **Terrestrial pipelines:** Water pipelines that transport the treated, potable water from the desalination plant to storage reservoirs or distribution networks, designed to maintain water quality and ensure reliable supply to water system.

vi. **Energy recovery devices:** Equipment used to capture and reuse hydraulic energy from the high-pressure brine stream generated in the RO process, significantly reducing the plant's overall energy consumption.

vii. **Chemical handling:** A system for the storage, preparation, and dosing of various chemicals used throughout the plant, such as coagulants.

viii. **Waste management facilities:** Infrastructure for the collection, treatment, and disposal of solid waste (sludge) generated during pre-treatment processes, including dewatering equipment, sludge storage, and handling systems for proper waste management.

ix. **Access roads:** Infrastructure for transportation and accessibility, allowing for the movement of personnel, materials, and equipment to and from the seawater reverse osmosis plant, facilitating construction, maintenance, and operational activities.

x. **Powerlines:** The network of electrical cables and associated infrastructure responsible for delivering power from the grid or local power generation sources to the desalination plant, ensuring a reliable and continuous supply of electricity for plant operations.

4.1.2 Development activities

i. **Marine intake:** a. Site selection and assessment to determine optimal location for intake structures. b. Seabed preparation and dredging to accommodate intake infrastructure. c. Construction and installation of intake structures, screens, and pumps.

ii. **Marine outfall:** a. Site selection and assessment for environmentally sound discharge location. b. Seabed preparation and dredging for outfall pipeline installation. c. Construction and installation of brine discharge pipelines.

iii. **Pre-treatment:** a. Design and layout of pre-treatment facilities. b. Construction of sedimentation basins, filtration units, and other required infrastructure. c. Installation of associated equipment, such as pumps, valves, and monitoring systems.

iv. **Plant facility:** a. Site preparation, including grading and levelling. b. Construction of the main facility, including foundations, walls, and roofing. c. Installation of SWRO trains, including high-pressure pumps, energy recovery devices, and membrane modules.

v. **Terrestrial Pipelines:** a. Route selection and land acquisition. b. Trenching or directional drilling for pipeline installation. c. Laying, welding, and pressure testing of pipeline segments.

vi. **Energy recovery devices:** a. Selection and procurement of appropriate devices. b. Installation within the RO system, including proper integration with high-pressure pumps and membrane modules. c. Calibration and testing to optimize energy efficiency.

vii. **Chemical handling:** a. Design and construction of chemical storage and dosing facilities. b. Installation of chemical storage tanks, pumps, and piping systems. c. Implementation of safety measures and monitoring systems for chemical handling.

viii. **Waste management facilities:** a. Design and layout of waste management infrastructure. b. Construction of sludge dewatering equipment, storage, and handling systems. c. Integration with the pre-treatment system and implementation of proper waste disposal methods.

ix. **Access roads:** a. Route planning and land acquisition for road construction. b. Grading, levelling, and excavation for roadbed preparation. c. Paving, striping, and installation of signage and drainage systems.

x. **Powerlines:** a. Route selection and land acquisition for powerline installation. b. Construction of electrical towers or poles and installation of insulators. c. Stringing of electrical cables and connection to the desalination plant's electrical system.

4.2 Mine wastewater

Mine wastewater, also known as AMD, is generated when sulphide minerals in the earth are exposed to air and water, resulting in acidic and metal-contaminated water. This wastewater is collected from the mining site to be treated.

4.2.1 Project components

i. **Wastewater collection system:** This component is responsible for gathering the mine wastewater, or AMD, from the mining site. It may include pipes, pumps, and storage tanks to collect and store the contaminated water before it undergoes treatment.

ii. **Pre-treatment system:** The pre-treatment system is designed to remove solid particles, debris, and larger contaminants from the mine wastewater before it is subjected to reverse osmosis. This step may involve sedimentation tanks, filtration units (such as sand or multimedia filters), and chemical treatment processes (such as coagulation and flocculation).

iii. **Reverse osmosis system:** This system uses a semipermeable membrane and applies pressure to force the mine wastewater through the membrane, effectively removing ions, molecules, and larger particles. The RO system includes high-pressure pumps, RO membranes, and associated plumbing and control systems.

iv. **Post-treatment system:** After the RO process, the water may require further treatment to ensure it meets the quality standards required for electrolysis. This may involve pH adjustment, additional filtration, or disinfection methods, such as ultraviolet (UV) treatment or chlorination.

Box 5: The Eastern Basin AMD plant on the Witwatersrand

The Eastern Basin plant is a large-scale AMD treatment plant located in Springs, South Africa. It has a capacity of 110 MLD making it one of the largest AMD treatment plants in the world. The plant, which was completed in 2016 and is operated by the Trans-Caledon Tunnel Authority, uses a combination of physical, chemical, and biological treatment processes to remove the pollutants from AMD water. It is designed to produce treated AMD water that meets the South African Department of Water and Sanitation drinking water standards. The Eastern Basin AMD plant was a major milestone in the management of AMD in South Africa and has helped to reduce the environmental impacts of AMD on the Eastern Basin and provided a source of clean water for the local community.

Image: https://www.miningreview.com/products-services/aecom-highly-commended-eastern-basin-acid-mine-drainage-plant/

4.2.2 Development activities

i. **Wastewater collection system:** a. Design and installation of wastewater collection infrastructure, such as pipes, pumps, and storage tanks. b. Site preparation, including excavation and grading. c. Connection to existing mine drainage infrastructure. d. Leak detection and monitoring systems installation.

ii. **Pre-treatment system:** a. Site preparation, including excavation and levelling. b. Construction of sedimentation tanks or basins. c. Installation of filtration units, such as sand or multimedia filters. d. Set up of chemical treatment processes, including coagulation and flocculation systems. e. Integration with the wastewater collection system.

iii. **Reverse osmosis system:** a. Site preparation, including excavation and levelling. b. Installation of high-pressure pumps and associated plumbing. c. Assembly and installation of RO membrane units, including support structures. d. Integration of control systems for monitoring and automation. e. Connection to the pre-treatment and post-treatment systems.

iv. **Post-treatment system:** a. Site preparation, including excavation and levelling. b. Installation of pH adjustment equipment, such as acid or alkali dosing systems. c. Set up of additional filtration units, if required. d. Installation of disinfection systems, such as UV treatment or chlorination equipment. e. Integration with the RO system.

v. **Electrolysis system:** a. Site preparation, including excavation and levelling. b. Installation of electrolysis equipment, such as electrolysers and associated power supply. c. Connection to the purified water supply from the post-treatment system. d. Set up of hydrogen storage and handling infrastructure, such as storage tanks and pipelines. e. Integration of monitoring and control systems for the electrolysis process.

5. Subsystem D: Ammonia via Haber-Bosch process

Green ammonia is produced via the Haber-Bosch process, where hydrogen from electrolysis reacts with nitrogen from the air under high pressure and temperature in the presence of an iron-based catalyst (Cabanga, 2022). The resulting ammonia is cooled and condensed before being stored in dedicated tanks or transported via pipelines, roads, or rail to domestic and international markets for fertiliser or energy storage.

Box 6: Green ammonia using Haber-Bosch, projects in the pipeline

As of July 2023, there are no large-scale ammonia plants using green hydrogen that are currently operational in the world. However, there are several projects in the pipeline which are expected to become operational in the next few years. Some of the most notable projects include:

- The Hendrina Renewable Energy Complex in Mpumalanga, South Africa, consisting of 2 x 200 MW wind farms, electricity grid corridors, a 150 MW electrolyser and an ammonia production facility.
- The Hive Green Ammonia plant, planned for Gqeberha in the Eastern Cape, which is expected to be operational by 2025. It will have a capacity of 150,000 tonnes of ammonia per year and will use renewable energy from solar and wind power to produce hydrogen.
- The HyGreen ammonia plant in Chile, which is being developed by Enel Green Power and is expected to be operational in 2023. It will have a capacity of 250,000 tonnes of ammonia per year and will use renewable energy from solar and wind power to produce the hydrogen.

5.1 Project components

i. **Hydrogen supply:** A reliable hydrogen supply system, which sources hydrogen from the Electrolyser facility, transports it to the ammonia production site, and stores it as needed.

ii. **Nitrogen production:** A nitrogen production unit, typically employing air separation technologies such as cryogenic distillation or pressure swing adsorption, to provide high-purity nitrogen required for ammonia synthesis.

iii. **Ammonia synthesis:** A reactor system utilizing the Haber-Bosch process or an alternative ammonia synthesis technology, where hydrogen and nitrogen are combined under high pressure and temperature to form ammonia. Assume footprint size of 2-4 ha (Cabanga, 2022).

iv. **Ammonia separation and purification:** A separation and purification unit, which removes unreacted gases and other impurities from the ammonia product stream, yielding high-purity ammonia. Assume 0.5 - 1 ha in footprint (Cabanga, 2022).

v. **Ammonia storage:** Storage facilities for the produced ammonia, which may include pressurized tanks, refrigerated storage tanks, or underground storage, depending on the project's scale and specific requirements.

vi. **Heat management system:** A heat management system, typically utilizing heat exchangers and cooling loops, to maintain optimal operating temperatures for the reactor and other process components.

vii. **Power supply:** A reliable power supply to provide electricity for the various process components, such as compressors, pumps, and control systems.

viii. **Control and monitoring system:** A centralized control and monitoring system that oversees the entire ammonia production process, ensuring optimal performance, monitoring key process parameters, and enabling early detection of potential issues.

ix. **Safety systems:** Safety systems, including pressure relief valves, gas detectors, and emergency shutdown systems, to ensure safe operation and mitigate potential hazards associated with ammonia production and handling.

x. **Balance of plant:** The balance of plant includes auxiliary components and infrastructure necessary to support the ammonia production process, such as piping, electrical connections, and mechanical supports.

5.2 Development activities

i. **Hydrogen supply:** a. Installation of hydrogen transportation infrastructure, such as pipelines or truck loading facilities. b. Construction of hydrogen storage facilities and connection to the electrolyser facility.

ii. **Nitrogen production:** a. Installation of air separation equipment and associated infrastructure. b. Integration with ammonia synthesis and hydrogen supply systems.

iii. **Ammonia synthesis:** a. Assembly and installation of ammonia synthesis reactor(s) and associated equipment. b. Connection to hydrogen and nitrogen supply systems.

iv. **Ammonia separation and purification:** a. Installation of separation and purification equipment, such as distillation columns or membrane separation systems. b. Integration with ammonia synthesis and storage systems.

v. **Ammonia storage:** a. Construction of ammonia storage facilities, including pressurized tanks, refrigerated tanks, or underground storage. b. Connection to the ammonia separation and purification system for efficient ammonia transfer.

vi. **Heat management system:** a. Installation of heat exchangers, cooling loops, and associated equipment. b. Integration with ammonia synthesis and other process components to maintain optimal operating temperatures.

vii. **Power supply:** a. Installation of electrical connections, transformers, and backup power systems as needed. b. Integration with control and monitoring systems for efficient power management.

viii. **Control and monitoring system:** a. Installation of control devices, sensors, and monitoring equipment. b. Setup and configuration of centralized control system for real-time monitoring and data analysis.

ix. **Safety systems:** a. Installation of safety equipment, including pressure relief valves, gas detectors, and emergency shutdown systems. b. Testing and calibration of safety systems to ensure proper functionality and responsiveness.

x. **Balance of plant:** a. Installation of auxiliary components, such as piping, electrical connections, and mechanical supports. b. Integration with ammonia synthesis and other systems to provide a cohesive and efficient ammonia production facility.

6. Subsystem E: Methanol via synthesis

Green methanol is produced through methanol synthesis, which involves reacting hydrogen from electrolysis with carbon dioxide (CO_2) or carbon monoxide (CO) under high pressure and temperature in the presence of a copper-zinc-aluminium catalyst. The CO_2 or CO can be sourced from industrial emissions or biomass gasification. The synthesised methanol is then purified, stored in dedicated tanks, and transported via pipelines, roads, or rail to domestic and international markets as a blending agent in aviation fuels or other applications.

Box 7: The George Olah Methanol Plant in Iceland

The George Olah Methanol Plant is a renewable methanol production facility located in Svartsengi, Iceland. It was commissioned in 2011 and is named after George Olah, a Nobel Prize-winning chemist who was a strong advocate for renewable energy. The plant uses carbon dioxide captured from industrial processes and renewable energy sources to produce renewable methanol. The methanol produced by the plant can be used as a clean fuel or as a raw material to produce green consumer goods. The plant was the world's first commercial CO_2-to-methanol plant when it was commissioned in 2012. It currently produces around 5 million litres of renewable methanol per year.

Image: https://www.carbonrecycling.is/project-goplant

6.1 Project components

i. **Hydrogen supply:** A reliable hydrogen supply system, which sources hydrogen from the electrolyser facility, transports it to the methanol production site, and stores it as needed.

ii. **CO_2 capture and supply:** A carbon dioxide capture system, which obtains CO_2 from renewable sources, such as direct air capture or biogenic sources, and transports it to the methanol production facility.

iii. **Methanol synthesis:** A reactor system utilizing methanol synthesis technologies, such as the synthesis gas (syngas) method, where hydrogen and carbon dioxide are combined under high pressure and temperature to form methanol.

iv. **Methanol separation and purification:** A separation and purification unit, which removes unreacted gases, water, and other impurities from the methanol product stream, yielding high-purity methanol.

v. **Methanol storage:** Storage facilities for the produced methanol, which may include atmospheric or pressurized storage tanks, depending on the project's scale and specific requirements.

vi. **Heat management system:** A heat management system, typically utilizing heat exchangers and cooling loops, to maintain optimal operating temperatures for the reactor and other process components.

vii. **Power supply:** A reliable power supply to provide electricity for the various process components, such as compressors, pumps, and control systems.

viii. **Control and monitoring system:** A centralized control and monitoring system that oversees the entire methanol production process, ensuring optimal performance, monitoring key process parameters, and enabling early detection of potential issues.

ix. **Safety systems:** Safety systems, including pressure relief valves, gas detectors, and emergency shutdown systems, to ensure safe operation and mitigate potential hazards associated with methanol production and handling.

x. **Balance of plant:** The balance of the plant includes auxiliary components and infrastructure necessary to support the methanol production process, such as piping, electrical connections, and mechanical supports.

6.2 Development activities

i. **Hydrogen supply:** a. Installation of hydrogen transportation infrastructure, such as pipelines or truck loading facilities. b. Construction of hydrogen storage facilities and connection to the electrolyser facility.

ii. **CO_2 capture and supply:** a. Installation of CO_2 capture equipment and associated infrastructure. b. Integration with methanol synthesis and hydrogen supply systems.

iii. **Methanol synthesis:** a. Assembly and installation of methanol synthesis reactor(s) and associated equipment. b. Connection to hydrogen and CO_2 supply systems.

iv. **Methanol separation and purification:** a. Installation of separation and purification equipment, such as distillation columns or membrane separation systems. b. Integration with methanol synthesis and storage systems.

v. **Methanol storage:** a. Construction of methanol storage facilities, including atmospheric or pressurized storage tanks. b. Connection to the methanol separation and purification system for efficient methanol transfer.

vi. **Heat management system:** a. Installation of heat exchangers, cooling loops, and associated equipment. b. Integration with methanol synthesis and other process components to maintain optimal operating temperatures.

vii. **Power supply:** a. Installation of electrical connections, transformers, and backup power systems as needed. b. Integration with control and monitoring systems for efficient power management.

viii. **Control and monitoring system:** a. Installation of control devices, sensors, and monitoring equipment. b. Setup and configuration of centralized control system for real-time monitoring and data analysis.

ix. **Safety systems:** a. Installation of safety equipment, including pressure relief valves, gas detectors, and emergency shutdown systems. b. Testing and calibration of safety systems to ensure proper functionality and responsiveness.

x. **Balance of plant:** a. Installation of auxiliary components, such as piping, electrical connections, and mechanical supports. b. Integration with methanol synthesis and other systems to provide a cohesive and efficient methanol production facility.

7. Transportation

This section will address transport options for the various PtX products; as well as a discussion around the health and safety aspects related to the transport of PtX products.

7.1 Road

For green hydrogen, transportation options include compressed hydrogen gas, liquid hydrogen, or in the form of chemical carriers such as ammonia or metal hydrides. Compressed hydrogen gas is the most common method, typically stored in high-pressure tanks on the truck. Liquid hydrogen requires cryogenic storage at extremely low temperatures (-253°C or -423°F), making it more complex and energy-intensive to transport. Ammonia can be transported as a liquid under moderate pressure or at low temperatures in specialized tanker trucks designed to handle its properties, including its corrosive nature and toxicity. Ammonia transportation requires adherence to strict safety guidelines to prevent leaks and minimize the risk of accidents. Methanol transportation is relatively straightforward, as it is a liquid at room temperature and pressure. It can be transported using specialized tanker trucks designed to handle its flammable and toxic properties. Like ammonia, transporting methanol requires following strict safety regulations to prevent spills and accidents.

Box 8: The AquaDuctus green hydrogen pipeline project

The AquaDuctus green hydrogen pipeline project, led by GASCADE and Fluxys, involves the construction of a 400 kilometres (km) offshore green hydrogen pipeline that will collect hydrogen from various production sites in the North Sea and transport it to Germany's coast, feeding it into the onshore hydrogen network. The project aims to boost Germany's energy security and become Germany's main hydrogen corridor by 2035, bringing in up to one million tonnes of hydrogen annually. The pipeline is expected to become a regulated open-access infrastructure available to all future hydrogen wind farm operators.

Image: https://www.innovationnewsnetwork.com/north-sea-green-hydrogen-pipeline-project-seeks-pci-status-from-european-commission/29185/

7.2 Rail

Rail transportation can be more efficient for long distances and larger volumes than truck transportation, leading to potential cost savings and reduced environmental impacts from reduced fuel consumption and emissions. However, rail transit times may be longer than those for road transportation, depending on network capacity and scheduling. Transporting green hydrogen, ammonia, and methanol via rail would require specialised railcars for each material. For compressed hydrogen gas or liquid hydrogen, pressurised or cryogenic tank railcars would be needed, respectively. Ammonia would require pressurised tank railcars designed to handle its corrosive and toxic properties. Methanol can be transported in standard liquid tank railcars that meet safety requirements for flammable and toxic liquids.

7.3 Pipelines

Pipeline transportation is generally more energy-efficient than road or rail transport, as it requires less energy per unit of material transported. This efficiency can lead to reduced GHG emissions and lower operating costs. But pipelines may offer less flexibility and scalability compared to road and rail transport, however, once the pipeline is in place, it can provide a continuous and reliable mode of transportation. Pipelines also require the construction and maintenance of a dedicated network of pipes, valves, pumps, and control systems to transport the materials from production facilities to storage sites or end-users. This infrastructure can be expensive to build and maintain, but it may be more cost-effective over long distances and for large volumes. Pipelines can have lower environmental impacts in terms of greenhouse gas emissions, air pollution, and noise pollution compared to road and rail transport. However, pipeline construction can lead to habitat fragmentation, land-use conflicts, and soil disturbance. Pipeline leaks or accidents can result in soil and water contamination, making it essential to have robust safety and monitoring systems in place. The permitting process for linear infrastructure in South Africa can be very complex, involving various stakeholders and addressing potential environmental and social concerns.

7.4 Health and safety during transport

The transportation of green hydrogen, ammonia, and methanol via road, rail, and pipeline presents various health and safety risks that must be carefully managed to minimize potential hazards. These risks are described in the sections that follow.

7.4.1 Green hydrogen

Hydrogen is highly flammable and can ignite in a wide range of air-fuel mixtures, posing a risk of fires or explosions during transportation. Green hydrogen gas can leak from containers or pipelines, potentially leading to asphyxiation if it displaces oxygen in confined spaces or mixes with air, forming a flammable mixture. It can also cause certain materials, such as metals, to become brittle, which may lead to structural failures in tanks, pipelines, or other transport equipment.

7.4.2 Green ammonia

Ammonia is a toxic and corrosive gas that can cause irritation and burns to the skin, eyes, and respiratory system upon contact or inhalation. High concentrations can be life-threatening. Leaks can occur during transportation, potentially causing hazardous exposure to humans or the environment. While less flammable than hydrogen, ammonia can still pose a risk of fires or explosions, particularly in confined spaces or when mixed with air at high concentrations.

7.4.3 Methanol

Methanol is a flammable liquid that can burn with an almost invisible flame, posing a risk of fires during transportation. It is toxic and can be absorbed through the skin, inhalation, or ingestion, leading to symptoms such as headache, dizziness, nausea, and even blindness or death in severe cases. Methanol spills can contaminate soil, water, and air, posing a risk to human health and the environment.

7.4.4 Transportation risks

Road, rail, and pipeline transportation of hazardous materials can result in accidents or spills, potentially exposing humans and the environment to harmful substances or causing fires and explosions. Increased traffic due to the transportation of hazardous materials by road or rail can raise the risk of accidents involving other vehicles and pedestrians, potentially leading to injuries or fatalities. Failures in transportation infrastructure, such as pipeline leaks or rail derailments, can pose risks to public health and safety, as well as environmental hazards.

8. PtX end-uses

Although this report has not included PtX end-uses within its scope of social and environmental impacts, this section briefly touches on the most likely end-uses in the South African context.

8.1 Green ammonia for energy storage

The process of using green ammonia for energy storage involves converting excess renewable energy into green ammonia and storing it. When electricity is needed, the stored green ammonia can be converted back into energy through ammonia cracking or direct combustion.

8.2 Green ammonia for fertilizer

Green ammonia can be used as a feedstock to produce nitrogen-based fertilizers. The most common fertilizers derived from ammonia include ammonium nitrate, urea, and ammonium sulphate.

Box 9: nuGen Zero Emission Haulage system

Anglo American has developed a hydrogen-powered truck, known as the nuGen Zero Emission Haulage system, which is retrofitted from a diesel-powered vehicle and employs a hybrid hydrogen fuel cell and battery pack. The truck has a load capacity of 290 t and weighs 220 t, with a total weight of 510 t. The plan is to retrofit 40 diesel trucks at Anglo's Mogalakwena platinum mine in Limpopo province, and later roll out the concept to all 400 haulage trucks in the fleet. The haul truck fleet accounts for 80% of diesel emissions at Anglo's mining sites, so a conversion to hydrogen/battery power will make a substantial contribution towards the group's target of carbon neutrality. The launch of the nuGen truck provides a real-world case for the wider adoption and use of hydrogen across the heaviest duty forms of transport, for which hydrogen carries numerous advantages over battery technology.

Image: https://www.moneyweb.co.za/in-depth/anglo-american/anglo-americans-hydrogen-powered-truck-is-a-head-turner/

8.3 Green methanol for sustainable aviation fuels (SAF)

Green methanol can be blended with conventional jet fuel to reduce the carbon footprint of aviation. It can also be utilised as a feedstock in various chemical and industrial processes, promoting a circular economy. Using green methanol to produce aviation fuel involves converting the green methanol into a sustainable aviation fuel (SAF) that can be blended with conventional jet fuel.

8.4 Green hydrogen for heavy industrial mobility

Hydrogen can be utilised as a clean and sustainable energy source for heavy industrial mobility by powering fuel cell electric vehicles. Heavy industrial mobility applications include transportation sectors such as heavy-duty trucks, buses, trains, ships, and off-road vehicles like forklifts and construction equipment. This electricity powers electric motors, which provide the propulsion needed for the vehicle. In this process, the only by-product is water vapor, making hydrogen fuel cell technology a zero-emission energy.

9. Impact identification

This section uses the DPSIR framework to present a high-level synopsis of the key environmental and social issues associated with a PtX economy.

9.1 DPSIR causal framework

Within each of the four identified issue clusters, a DPSIR causal framework was used to identify the key system elements comprising: driving forces, pressures, states, impacts and responses (note that this report presents a version of DPSIR, since many different interpretations of DPSIR exist and are dependent on the context).

9.1.1 Driving forces

Driving forces are the global and domestic trends pushing forward a South African PtX economy. Four drivers were identified:

1. Techno-economic feasibility – Major global advancements in RE, RO and PtX technologies.
2. Need for energy security – Increased geopolitical risks and energy shortages at global scale, increased energy scarcity in South Africa.
3. Need for jobs and economic growth – Urgent national need and commitment to reduce poverty and unemployment.
4. Need to reduce GHG emissions – Global and national need and commitment to reduce GHG emissions.

9.1.2 Pressures

Pressures, as defined in this report, are the direct mechanisms through which PtX activities and infrastructure will positively and/or negatively affect people and the environment. Five pressures were identified:

1. Financial investment – Direct capital inflows from foreign or private sector investors.
2. Land-use planning – Regulatory decisions/land use policies guiding the nature and extent of PtX projects.
3. Land use change – Potential change from greenfield or agricultural uses to facilities and infrastructure for PtX projects.
4. Infrastructure construction – Construction activities associated with initial project development.
5. Operational and maintenance activities – Day-to-day operational and maintenance activities associated with ongoing production.
6. PtX transportation – PtX logistics via rail, road, pipeline, port, and powerline.

9.1.3 States

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, like governance. Seven different states were identified (Table 2).

Table 4: Baseline receiving environment states across South Africa which might be influenced by a PtX economy

State		Explanation	Regional examples
S1	**REDZs (Regional)**	Rural; green fields; relatively stable soils; water-constrained; farming with some tourism; high unemployment and poverty; resource-constrained municipalities; deteriorating urban centres and infrastructure	REDZ 8 Cookhouse, REDZ 3 Springbok
S2	**Coastal SEZs (Regional)**	Sensitive coastal zones located around SEZs; unstable soils/coastal sediments; water-constrained; green-/brownfields; decent infrastructure, services, and municipal capacity	Saldanha Bay, Richards Bay, Boegoebaai, Coega
S3	**Inland mining zones (Regional)**	Often disturbed lands; brownfields; unstable soils; polluted water; poor air quality; aged infrastructure; high unemployment and poverty; resource-constrained municipalities; deteriorating urban centres and infrastructure	Older mining areas e.g., Witbank and Ermelo in Mpumalanga Province
S4	**PtX transport corridors (Regional & national)**	Distributed servitude networks between infrastructure and manufacturing nodes; rural/urban; often ecologically sensitive; deteriorating infrastructure - road, rail, powerline, pipeline, ports	
S5	**Energy security (National)**	Crisis stage, chronic scarcity, load-shedding more intense than ever, reliance on coal	
S6	**GHG emissions (National)**	90% reliance on coal for electricity, large baseline GHG emissions, slowly integrating renewable energy into system	
S7	**Economy (National)**	High unemployment; high inequality, low growth	
S8	**Governance conditions (National)**	Low skills, low confidence; high corruption; low trust	

9.1.4 Issues and impacts

Impacts are net positive or negative effects on biophysical and social environments. Ten impacts were identified:

1. Habitats and species
2. GHG emissions
3. Economic growth
4. Services and infrastructure
5. Land use conflict
6. Jobs and skills
7. Human health
8. Sense of place
9. Water availability
10. Erosion/sediment movement

From these 10 issues/impacts, we cross references them with reference to the peer reviewed and grey literature covering the topic of environmental and social impacts that manifest with the technology sub-systems described.

Table 5: Synthesis of the key headline issues which emerged from the WG scoping and literature review exercises

Issue	Impacts	Literature source/s
Macro-socioeconomics and greenhouse gases	Economic growth	(Fazioli and Pantaleone, 2021) (DTIC, 2022); (Hamukoshi et al., 2022) (Siemens Energy, 2021) (DSI, 2021) (Alzoubi, 2021)
	Greenhouse gases	(Oliveira, Beswick and Yan, 2021) (AbouSeada and Hatem, 2022) (Derwent, 2023) (Sand et al., 2023)
Local socioeconomics and livelihoods	Services and infrastructure	(CSIR, 2022) (Cabanga, 2022) (CSIR, 2023)
	Jobs and skills	(IHS Markit, 2021) (DTIC, 2022) (DSI, 2021)
	Human health	(Sheikh, Kocaoglu and Lutzenhiser, 2016) (Vallejos-Romero et al., 2023) (USDOE, 2023).
	Sense of place	(Maehr et al., 2015) (Haddad et al., 2018)
Ecology and biodiversity	Habitats and species	(Weidner, Tulus and Guillén-Gosálbez, 2023) (Lattemann and Höpner, 2008) (Hamed and Alshare, 2022) (CSIR, 2022) (Cabanga, 2022) (WSP, 2022)
Land uses, land care and water resources	Land use conflict	(Hamed and Alshare, 2022) (Rabaia et al., 2021) (Sheikh, Kocaoglu and Lutzenhiser, 2016) (Jensen et al., 2018)
	Water availability	(CSIR, 2022) (Cabanga, 2022) (WSP, 2022)
	Erosion/sediment movement	(Hamed and Alshare, 2022) (CSIR, 2022) (CSIR, 2023)

9.1.5 Responses

Responses are the options available for society to mitigate negative impacts and enhance positive ones. Eleven different responses classes were identified.

Table 6: The different classes of response options which might be used to mitigate and enhance impacts

Response class		Examples
R1	**Avoidance**	Avoiding highly sensitive ecological areas and cultural heritage sites (screening undertaken before EIA phase)
R2	**Impact mitigation**	Reducing negative impacts if avoidance is not possible through thoughtful design and implementation, as well as thorough and consistent monitoring of the effectiveness of impact mitigation measures
R3	**Restoration**	Restoring damaged ecological habitats to their original state after disturbance
R4	**Offsetting**	Compensating for residual impacts on the environment by enhancing or restoring equivalent habitats elsewhere
R5	**Co-locations**	Mixed land-use synergies e.g., agrivoltaics which involves the use of land for both solar panels and agriculture
R6	**Community engagement**	Actively involving local communities in decision-making processes related to land use, for example
R7	**Good governance**	Policy clarity, government efficiency, transparency, credibility, participatory decision-making
R8	**Economic instruments**	Privatisation, incentives, subsidies, taxes, capital investment
R9	**International collaboration**	Collaborating with other nations to, for example, share knowledge, technology, and resources
R10	**Knowledge instruments**	Research and skills development, including technical innovation, training, and reskilling
R11	**Regulatory instruments**	Where regulations could be passed to minimise potential harm or increase the benefits of proposed developments

An integration of the key DPSIR relationships is presented in Figure 2 below.

In the section which follows, all the identified DPSIR relationships (from pressures to impacts), for each issue cluster, are tabulated and then have been transposed into CLDs.

The primary elements of the CLDs include:

- **Drivers:** Generic across all diagrams, top left.
- **Pressures:** Dark grey boxes, flow from technology types into direct mechanism of pressure.
- **States:** Yellow boxes under impacts. Coded S1 to S7. The state of the receiving environment where the impact manifests.
- **Impacts:** Blue boxes. The net impacts to people and the environment emanating from the pressures.
- **Responses:** Light grey boxes. Coded R1 to R11. Displayed on the polarity connections between pressures and impacts demonstrating points of potential intervention.
- **Polarity:** The connection lines between pressures and impacts. Green lines are desirable relationships. Orange lines are undesirable relationships.
- **Feedbacks:** Blue connection lines demonstrating feedbacks between impacts where one impact leads to more of another impact, and vice versa.

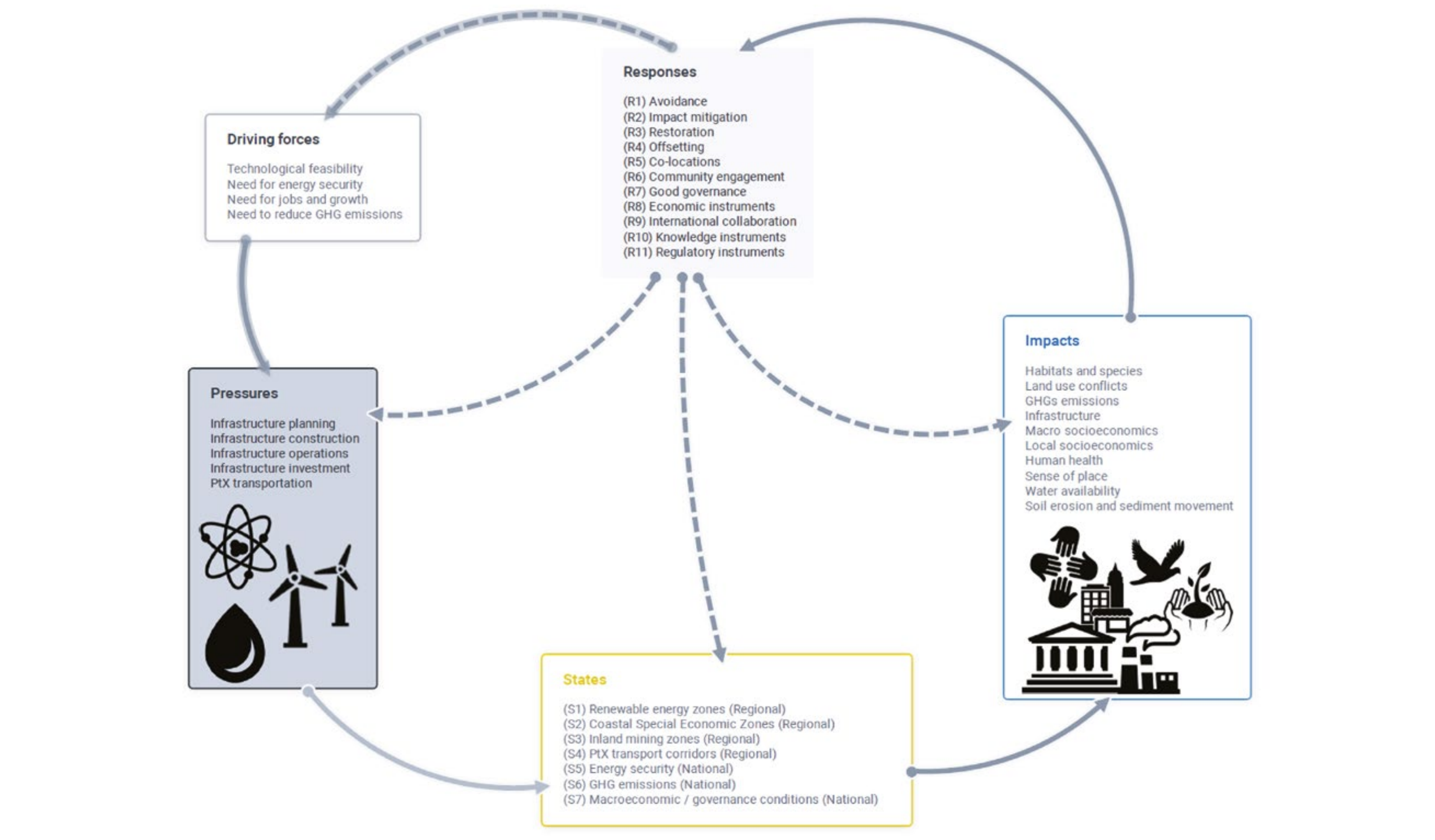

Figure 2: DPSIR summary diagram showing the conceptual relationships evident in a South African PtX economy between drivers, pressures, states, impacts and responses. (Created with Plectica.com)

9.2 Macro-socioeconomics and greenhouse gases

Table 7: Macro-socioeconomics and greenhouse gases pressures, states, impacts, relationships, and potential responses

Pressures (description)		State	Impacts	Relationship	Responses
RE operations	(Decarbonised electricity generation)	S6	GHGs	(+)	Economic instruments, international collaborations, regulatory instruments
RE operations	(Oversized generation)	S5	Services and infrastructure	(+)	Economic instruments, good governance, regulatory instruments
RE operations	(Not oversized generation)	S5	Services and infrastructure	(-)	Regulatory instruments, economic instruments
RE investment	(Foreign govts, private sector)	S7	Economic growth	(+)	Economic instruments, international collaborations, good governance
SWRO investment	(Foreign govts, private sector)	S7	Economic growth	(+)	Economic instruments, international collaborations, good governance
MWRO investment	(Foreign govts, private sector)	S7	Economic growth	(+)	Economic instruments, international collaborations, good governance

Pressures (description)		State	Impacts	Relationship	Responses
PtX operations	(Fugitive emissions, leaks/purges)	S6	GHGs	(-)	Impact mitigation, regulatory instruments
PtX investment	(Foreign govts, private sector)	S7	Economic growth	(+)	Economic instruments, international collaborations, good governance
PtX operations	(Revenues, supply chains, markets)	S7	Economic growth	(+)	Economic instruments, knowledge instruments, regulatory instruments
PtX transport	(Fugitive emissions from leaks)	S6	GHGs	(-)	Impact mitigation, regulatory instruments
PtX transport	(Capital spends)	S4	Services and infrastructure	(+)	Economic instruments, good governance

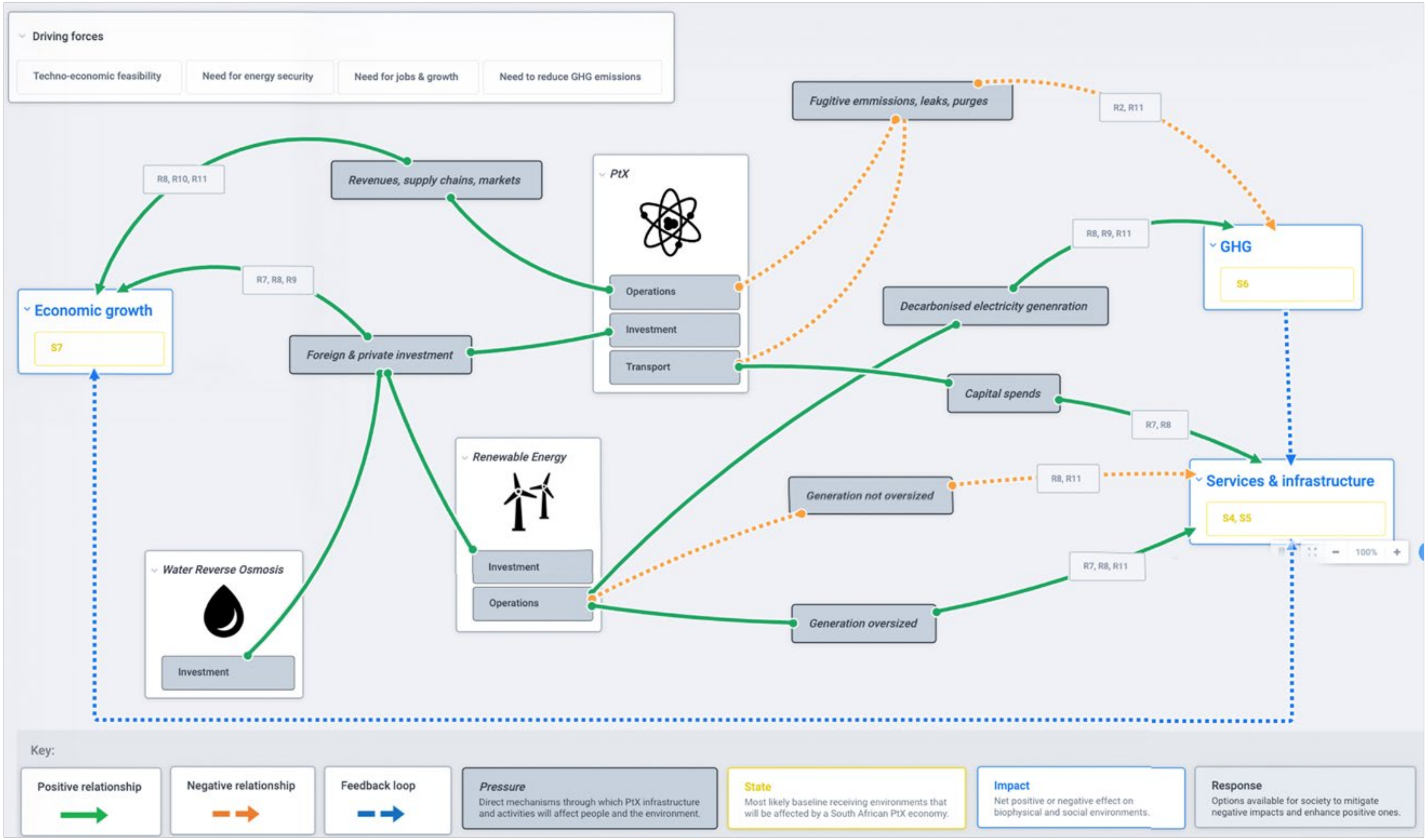

Figure 3: Macro-socioeconomics and greenhouse gases pressure-impact diagram (Created with Plectica.com)

9.3 Local socioeconomics and livelihoods

Table 8: Local socioeconomics and livelihoods pressures, states, impacts, relationships and potential responses

Pressures (description)		State	Impacts	Relationship	Responses
RE investment	(New businesses & infrastructure)	S1	Jobs & skills	(+)	Economic instruments, regulatory instruments, good governance
RE construction/ operations	(Supply chains, jobs, skills development)	S1	Jobs & skills	(+)	Economic instruments, knowledge instruments, regulatory instruments
RE construction/ operations	(Job seeker in-migration, strains on services & municipalities)	S1	Services and infrastructure	(-)	Impact mitigation, community engagement, economic instruments
RE construction/ operations	(Landscapes, aesthetics & heritage resources)	S1	Sense of place	(-)	Avoidance, impact mitigation, community engagement, offsets
RE operations	(Human health effects e.g., noise, flicker, glare etc.)	S1	Human health	(-)	Avoidance, impact mitigation, community engagement, regulatory instruments
RE operations	(Displacing electricity from coal mining/ burning)	S3	Human health	(+)	Economic instruments, regulatory instruments, good governance

Pressures (description)		State	Impacts	Relationship	Responses
MW/SWRO investment	(New businesses & infrastructure)	S1	Jobs & skills	(+)	Economic instruments, regulatory instruments, good governance
SWRO construction/ operations	(Supply chains, jobs, skills development)	S2	Jobs & skills	(+)	Knowledge instruments, international collaborations, economic instruments
SWRO construction/ operations	(Landscapes, aesthetics & heritage resources)	S2	Sense of place	(-)	Avoidance, impact mitigation, community engagement, offsets
SWRO operations	(Effects of brine discharge, communities who use marine resources)	S2	Jobs & skills	(-)	Avoidance, impact mitigation, community engagement, regulatory instruments
MWRO construction	(Investment in aged mines and infrastructure)	S3	Services and infrastructure	(+)	Economic instruments, regulatory instruments, community engagement
MWRO construction/ operations	(Supply chains, jobs, skills development)	S3	Jobs & skills	(+)	Knowledge instruments, international collaborations, economic instruments
MWRO operations	(Reduction of AMD, reduced human exposure)	S3	Human health	(+)	Regulatory instruments, community engagement, knowledge instruments

Pressures (description)		State	Impacts	Relationship	Responses
PtX investment	(Investment into South Africa SEZs and businesses)	S2	Jobs & skills	(+)	Economic instruments, good governance, international collaborations
PtX construction/ operations	(Supply chains, jobs, skills development)	S2	Jobs & skills	(+)	Economic instruments, knowledge instruments, regulatory instruments
PtX operations	(Exposure through explosions, leaks and spills)	S2	Human health	(-)	Impact mitigation, community engagement, economic instruments, regulatory instruments
PtX transport	(Public use of new transport infrastructure)	S4	Services and infrastructure	(+)	Economic instruments, good governance, community engagement
PtX transport	(Traffic, noise, dust, pedestrian collisions, accidents)	S4	Human health	(-)	Impact mitigation, community engagement, economic instruments, regulatory instruments
PtX Transport	(Exposure through explosions, leaks and spills)	S4	Human health	(-)	Impact mitigation, community engagement, economic instruments, regulatory instruments

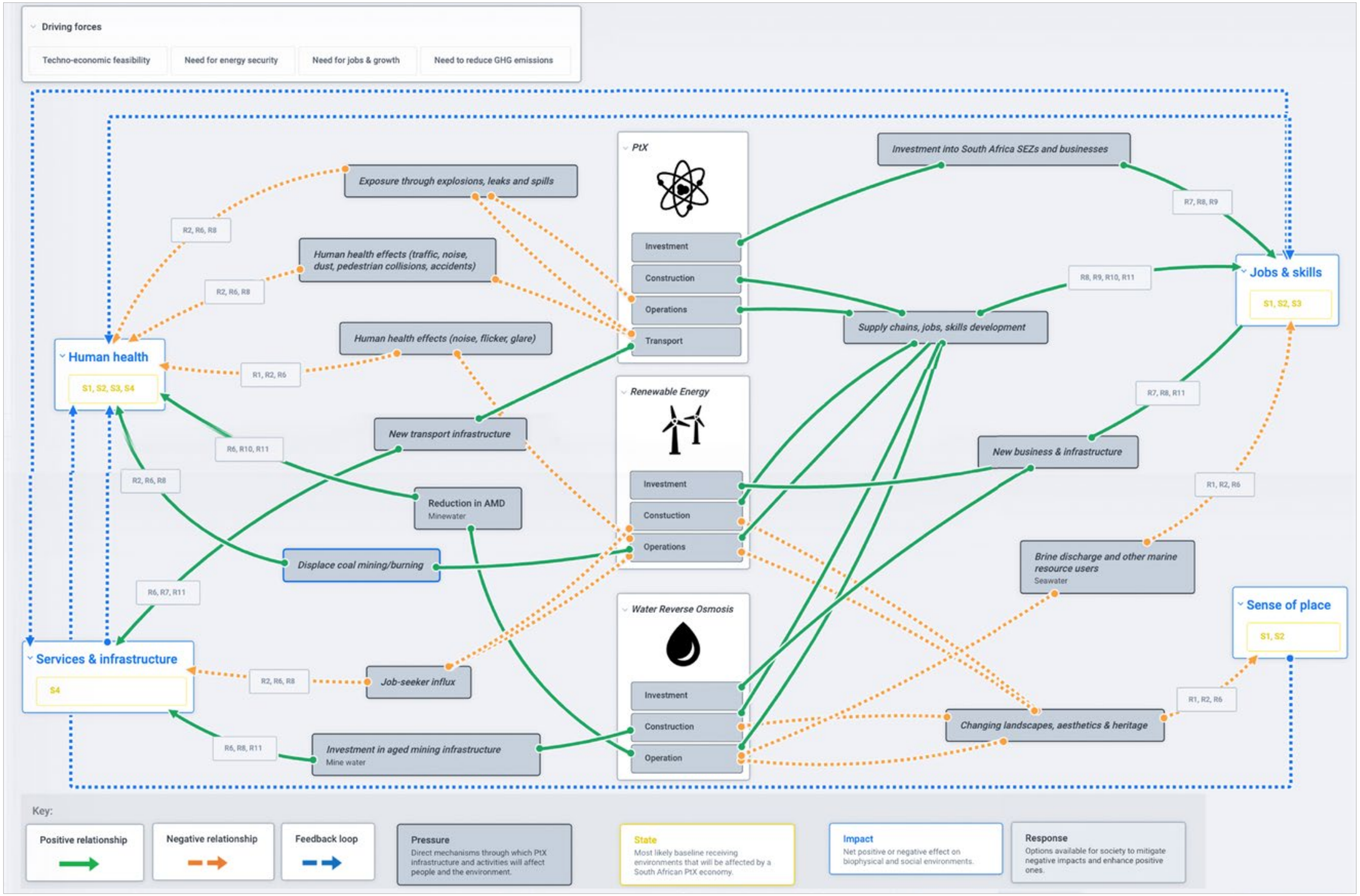

Figure 4: Local socioeconomics and livelihoods pressure-impact diagram (Created with Plectica.com)

9.4 Ecology and biodiversity

Table 9: Ecology and biodiversity pressures, states, impacts, relationships and potential responses

Pressures (description)		State	Impacts	Relationship	Responses
RE construction	(Vegetation clearance)	S1	Habitats & species	(-)	Avoidance, impact mitigation, restoration, offsetting
RE operations	(Turbines blades, avifauna collisions)	S1	Habitats & species	(-)	Avoidance, impact mitigation
RE operations	(Displacing electricity from coal mining/ burning)	S3	Habitats & species	(+)	Economic instruments, regulatory instruments
RE land use planning	(Conflicts with conservation planning)	S1	Land use conflict	(-)	Avoidance, offsetting, regulatory instruments
SWRO construction	(Vegetation clearance)	S2	Habitats & species	(-)	Avoidance, impact mitigation, restoration, offsetting
SWRO operations	(Brine disposal)	S2	Habitats & species	(-)	Avoidance, impact mitigation
SWRO operations	(Sediment erosion/ accretion)	S2	Habitats & species	(-)	Avoidance, impact mitigation
SWRO land use planning	(Conflicts with conservation planning)	S2	Land use conflict	(-)	Avoidance, offsetting, community engagement

Pressures (description)		State	Impacts	Relationship	Responses
MWRO operations	(Reduction in AMD in hydrological system)	S3	Habitats & species	(+)	Economic instruments, regulatory instruments
PtX planning	(Conflicts with conservation planning)	S2	Land use conflict	(-)	Avoidance, offsetting, , community engagement
PtX construction	(Vegetation clearance)	S2	Habitats & species	(-)	Avoidance, impact mitigation, restoration, offsetting
PtX operations	(Contamination via explosions, leaks and spills)	S3	Habitats & species	(-)	Avoidance, impact mitigation
PtX transport	(Vegetation clearance)	S4	Habitats & species	(-)	Avoidance, impact mitigation, restoration, offsetting
PtX transport	(Trucks, powerlines, avifauna collisions)	S4	Habitats & species	(-)	Avoidance, impact mitigation
PtX transport	(Contamination via explosions, leaks and spills)	S4	Habitats & species	(-)	Avoidance, impact mitigation, regulatory instruments

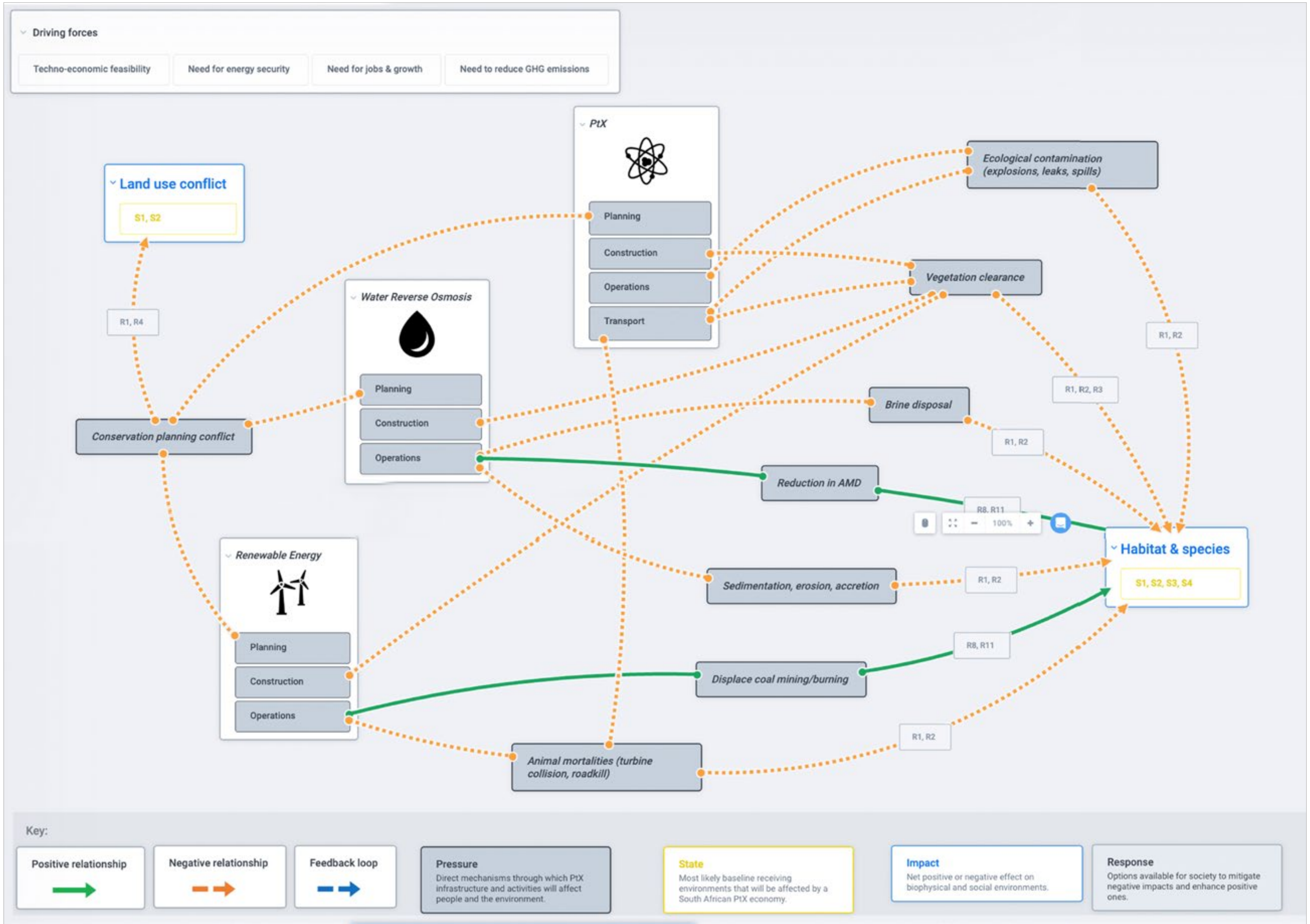

Figure 5: Ecology and biodiversity pressure-impact diagram (Created with Plectica.com)

9.5 Land uses, land care and water resources

Table 10: Land uses, land (coast and ocean) care and water resources pressures, states, impacts, relationships, and potential responses

Pressures (description)		State	Impacts	Relationship	Responses
RE land use planning	(Overlaps with tourism & farming)	S1	Land use conflict	(-)	Avoidance, impact mitigation, community engagement, co-location
RE construction/ operations	(In-migration, stock theft, fires)	S1	Land use conflict	(-)	Community engagement, knowledge instruments, impact mitigation
RE construction	(Vegetation clearance, soil instability & erosion)	S1	Land care	(-)	Avoidance, impact mitigation, restoration
RE construction/ operations	Water consumption	S1	Water availability	(-)	Avoidance, impact mitigation, regulatory instruments
SWRO land use planning	(Public/ subsistence/ tourist access to the beach)	S2	Land use conflict	(-)	Avoidance, impact mitigation, community engagement, regulatory instruments
SWRO construction	(Vegetation clearance, soil instability & erosion)	S2	Land care	(-)	Avoidance, impact mitigation, restoration
SWRO operations	(Marine infrastructure, altered sediment dynamics)	S2	Land care	(-)	Avoidance, impact mitigation, restoration

Pressures (description)		State	Impacts	Relationship	Responses
SWRO operations	(Oversize plant, water for other industries)	S2	Water availability	(+)	Economic instruments, regulatory instruments, community engagement
MWRO construction	(Vegetation clearance, soil instability & erosion)	S3	Land care	(-)	Avoidance, impact mitigation, restoration
MWRO operations	(Reduction of AMD, more water for industries)	S3	Water availability	(+)	Co-location, economic instruments, regulatory instruments
PtX land use planning	(Competition for prime property within SEZs)	S4	Land use conflict	(-)	Avoidance, community engagement, economic instruments
PtX construction	(Vegetation clearance, soil instability & erosion)	S4	Land care	(-)	Avoidance, impact mitigation, restoration
PtX operations	(Contamination via explosions, leaks and spills)	S4	Water availability	(-)	Avoidance, impact mitigation, economic instruments, regulatory instruments
PtX transport	(Vegetation clearance, soil instability & erosion)	S4	Land care	(-)	Avoidance, impact mitigation, restoration
PtX transport	(Contamination via explosions, leaks and spills)	S4	Water availability	(-)	Avoidance, impact mitigation, economic instruments

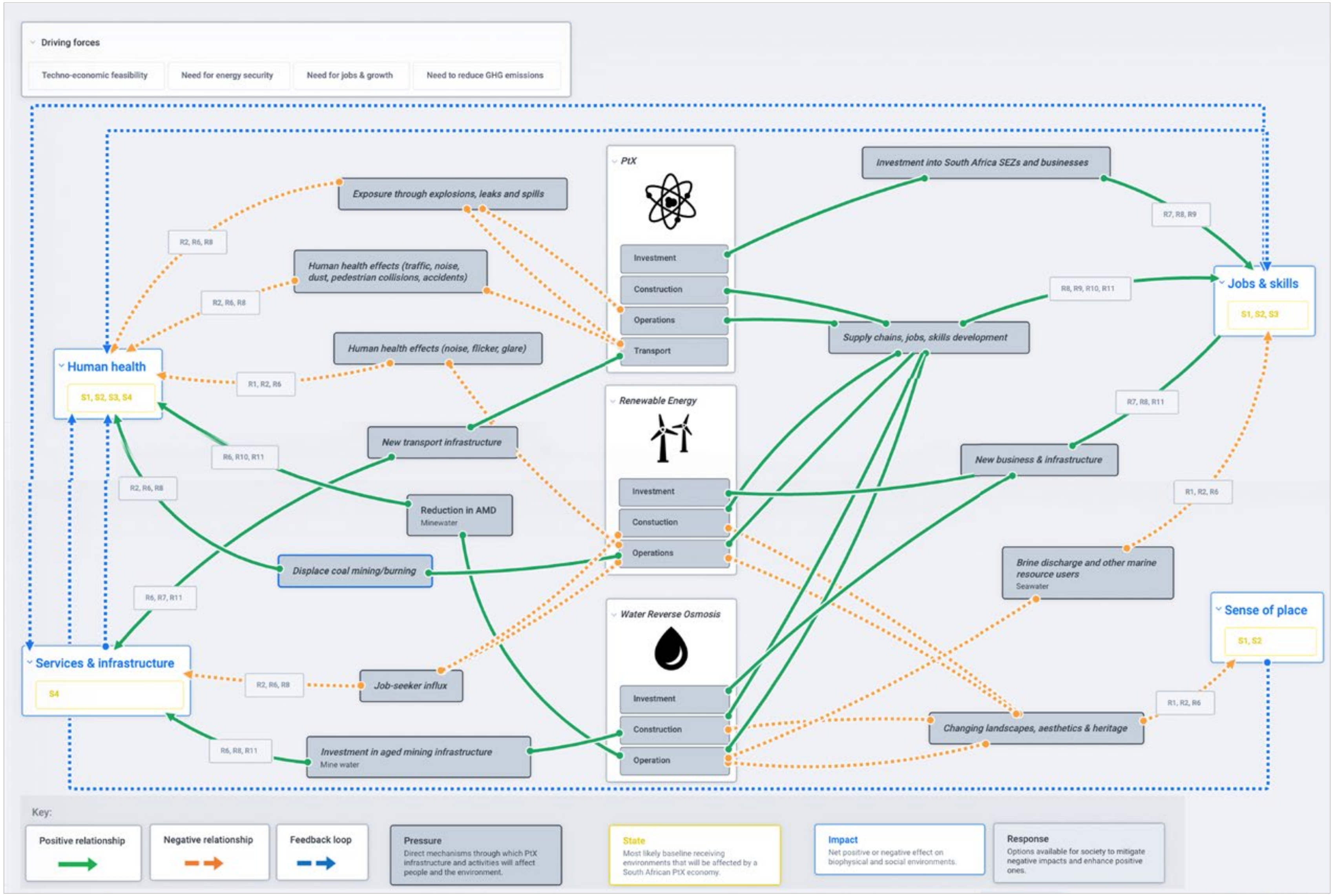

Figure 6: Land uses, land care and water resources pressure-impact diagram (Created with Plectica.com)

10. Impact assessment

10.1 Survey statements

Table 11: Survey statements distributed to WG members. For positive impacts (green), WG members had to rate their levels of optimism on a Likert Scale (1-3). For negative impacts (orange), WG members had to rate their levels of concern on a Likert Scale (1-3).

Impact	Survey statement on possible future outcomes for South Africa
(+)	1. Renewable energy generation and use of green PtX products decarbonise South Africa's energy economy
(+)	2. Energy from PtX projects displace fossil fuels, improving the environmental quality of regions e.g., Mpumalanga, where coal mining, coal combustion, and AMD are prevalent
(+)	3. Investment into PtX projects creates new revenues, markets, and supply chains, leading to economic growth and renewed confidence in the Just Transition
(+)	4. Capital spends on PtX-related transport (rail, roads, ports, pipelines, powerlines) create superior quality infrastructure at important transport networks and nodes e.g., national road connections, railway links, and ports
(+)	5. Construction and operations of PtX projects create new businesses, supply chains, and jobs and skills for local people in the regions within which they occur
(+)	6. Investment into PtX projects leads to better local infrastructure and services e.g., roads, water supply, wastewater treatment etc.
(-)	7. Fugitive emissions, leaks, and purges from PtX project operations and transportation lead to increased GHG emissions
(-)	8. Job seeker and labourer in-migration during PtX project construction and operations place strain on already constrained municipalities, services, and infrastructure
(-)	9. Renewable energy construction and operations, and electricity transmission (powerlines) in rural, agricultural landscapes lead to changes in aesthetics and heritage resources, causing an altered sense of place
(-)	10. Renewable energy construction and operations, and electricity transmission (powerlines) in rural, agricultural landscapes lead to vegetation clearance and the loss of habitats and species

Impact	Survey statement on possible future outcomes for South Africa
(-)	11. Renewable energy construction and operations, and electricity transmission (powerlines) in regions that depend economically on agriculture and tourism contribute to loss of local incomes
(-)	12. SWRO construction, operations, and transport (pipelines) within coastal environments lead to changes in aesthetics and heritage resources, causing an altered sense of place
(-)	13. Brine from SWRO operations discharged to the marine environment causes a loss of habitat and species, affecting marine living resources and the people who depend on them
(-)	14. SWRO construction, operations, and transport (pipelines) in coastal zones lead to vegetation clearance and the loss of habitats and species
(-)	15. Authorising SWRO construction in coastal regions leads to constrained public access to the beach and coastal resources
(-)	16. SWRO operational infrastructure alters coastal sediment movement regimes, causing coastline accretion and erosion
(-)	17. PtX project construction and operations cause nuisance impacts to human health e.g., flicker, glare, noise, traffic, dust etc.
(-)	18. Explosions, leaks, and spills at PtX project operations, or during transport and handling, contribute toward human death or injury and ecological contamination
(-)	19. Traffic, noise, dust, and physical collisions during PtX project construction and operations and transportation lead to loss of habitats and species e.g., faunal collisions on roads
(-)	20. PtX project linear infrastructure construction (roads, rail, pipelines, powerlines) leads to vegetation clearance causing a loss of habitat and species
(-)	21. PtX project construction and operational activities (renewable energy, desalination, transport infrastructure) lead to soil instability and soil erosion
(-)	22. Turbine blades used at operational wind farms lead to bird and bat mortality
(-)	23. Developing PtX projects and transport corridors (roads, rail, pipelines, powerlines) in regions that would otherwise be used for conservation planning leads to land-use conflict
(-)	24. Use of scarce water resources during renewable energy construction and operations (e.g., for PV panel washing, human consumption for staff etc.) in rural, water-stressed regions leads to increased water scarcity
(-)	25. Authorising PtX projects and increasing competition within SEZs for prime property with port access leads to land use conflict

10.2 Survey results

10.2.1 Positive (desirable) impacts

Survey statement	Mean (σ)	Median
Renewable energy generation and use of green PtX products decarbonise South Africa's energy economy	2.55 (0.52)	Very optimistic
Investment into PtX projects creates new revenues, markets, and supply chains, leading to economic growth and renewed confidence in the Just Transition	2.45 (0.52)	Optimistic
Construction and operations of PtX projects create new businesses, supply chains, and jobs and skills for local people in the regions within which they occur	2.36 (0.81)	Very optimistic
Capital spends on PtX-related transport (rail, roads, ports, pipelines, powerlines) create superior quality infrastructure at important transport networks and nodes e.g., national road connections…	2.27 (0.65)	Optimistic
Energy from PtX projects displace fossil fuels, improving the environmental quality of regions e.g., Mpumalanga, where coal mining, coal combustion, and AMD are prevalent	2.18 (0.75)	Optimistic
Investment into PtX projects leads to better local infrastructure and services e.g., roads, water supply, wastewater treatment etc.	2 (0.77)	Optimistic

10.2.2 Negative (undesirable) impacts

Survey statement	Mean (σ)	Median
Turbine blades used at operational wind farms lead to bird and bat mortality	2.36 (0.67)	Concerned
Brine from SWRO operations discharged to the marine environment causes a loss of habitat and species, affecting marine living resources and the people who depend on them	2.18 (0.75)	Concerned
Job seeker and labourer in-migration during PtX project construction and operations place strain on already constrained municipalities, services, and infrastructure	2.09 (0.70)	Concerned
Renewable energy construction and operations, and electricity transmission (powerlines) in rural, agricultural landscapes lead to vegetation clearance and the loss of habitats and species	2.09 (0.83)	Concerned
SWRO construction, operations, and transport (pipelines) in coastal zones lead to vegetation clearance and the loss of habitats and species	2.09 (0.70)	Concerned
Developing PtX projects and transport corridors (roads, rail, pipelines, powerlines) in regions that would otherwise be used for conservation planning leads to land-use conflict	2.09 (0.83)	Concerned
Fugitive emissions, leaks, and purges from PtX project operations and transportation lead to increased greenhouse gas emissions	2 (0.77)	Concerned
SWRO operational infrastructure alters coastal sediment movement regimes, causing coastline accretion and erosion	2 (0.77)	Concerned
Explosions, leaks, and spills at PtX project operations, or during transport and handling, contribute toward human death or injury and ecological contamination	2 (0.63)	Concerned
Renewable energy construction and operations, and electricity transmission (powerlines) in regions that depend economically on agriculture and tourism contribute to loss of local incomes	1.91 (0.94)	Concerned

Survey statement	Mean (σ)	Median
PtX project linear infrastructure construction (roads, rail, pipelines, powerlines) leads to vegetation clearance causing a loss of habitat and species	**1.91 (0.83)**	**Concerned**
Renewable energy construction and operations, and electricity transmission (powerlines) in rural, agricultural landscapes lead to changes in aesthetics and heritage resources, causing an altered sense of place	**1.82 (0.87)**	**Concerned**
Traffic, noise, dust, and physical collisions during PtX project construction and operations and transportation lead to loss of habitats and species e.g., faunal collisions on roads	**1.82 (0.75)**	**Concerned**
SWRO construction, operations, and transport (pipelines) within coastal environments lead to changes in aesthetics and heritage resources, causing an altered sense of place	**1.73 (0.79)**	**Concerned**
Use of scarce water resources during renewable energy construction and operations (e.g., for PV panel washing, human consumption for staff etc.) in rural, water-stressed regions leads to increased water scarcity	**1.73 (0.79)**	**Concerned**
Authorising SWRO construction in coastal regions leads to constrained public access to the beach and coastal resources	**1.45 (0.69)**	**Not concerned**
PtX project construction and operational activities (renewable energy, desalination, transport infrastructure) lead to soil instability and soil erosion	**1.45 (0.69)**	**Not concerned**
PtX project construction and operations cause nuisance impacts to human health e.g., flicker, glare, noise, traffic, dust etc.	**1.36 (0.50)**	**Not concerned**
Authorising PtX projects and increasing competition within SEZs for prime property with port access leads to land use conflict	**1.36 (0.67)**	**Not concerned**

11. Recommendations

The following section details some of the principles and practices which should guide decision-making for PtX projects in South Africa going forward.

11.1 Precautionary approach to decision-making

A thoughtfully designed PtX economy would likely bring significant changes to South Africa's social, economic, political, and environmental systems. The transition could drive job creation, economic growth, and increased trust in South African governance, while reducing the country's carbon emissions and dependence on fossil fuels. All these outcomes are theoretically possible, so too are undesirable outcomes if infrastructure is developed with inadequate consideration given to sensitive social and ecological receiving environments and to the creation of local employment opportunities. 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 an protracted period of time. 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 EIA, for project-level guidance.

11.1.1 Policy/programme-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.

The SEA would take around 12-24 months to be completed (depending on the scope) and it is recommended that it focus spatially on one or several regional hubs proposed for PtX development around South Africa's SEZs. The study should consider all development aspects and activities associated with a South African PtX economy, ranging from enabling infrastructure (e.g., renewable energy and SWRO), 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. It is recommended that preliminarily outputs for PtX SEA would include, *inter alia:*

- Development of PtX production and export scenarios, from which it would be possible to properly estimate macro and local socio-economic impacts, and potential changes to regional ecology, undertaken through landscape modelling (based on the quantitative manufacturing and export scenarios).
- Based on factors such as resource availability, socio-economic, ecological and infrastructure features, identify PtX development zones where PtX-related projects could be streamlined in terms of EIA requirements and timeframes, allowing for quicker integration into the South African energy economy.
- Identify regions unsuitable (no-go) for PtX development activities based on the sensitivity of their social and ecological receiving environments.

Given South Africa's diverse landscapes, cultural heritage, socio-economic challenges, and the strategic importance of its SEZs, using an SEA for PtX development would offer several benefits:

1. **Holistic approach:** A scenarios-based SEA would allow for a comprehensive understanding of the cumulative and synergistic impacts of multiple PtX projects. It would consider direct, indirect, and secondary impacts, which are likely to be overlooked in project-level assessments.
2. **Informed decision making:** By developing production and export scenarios, decision-makers can weigh different outcomes and implications of PtX projects, making it possible to choose the most sustainable and beneficial options.
3. **Streamlined processes:** Identifying zones suitable for streamlined EIA processes would make it easier and faster for developers to obtain approvals, boosting investor confidence and expediting development.
4. **Protection of sensitive areas:** Determining areas unsuitable for PtX based on their ecological and social sensitivity, among other factors, ensures that the rich biodiversity and cultural heritage of South Africa are protected. This also reduces the risk of conflict with local communities and stakeholders.
5. **Cross-sectoral integration:** The SEA would provide a platform for integrating environmental considerations with other sectors such as agriculture, tourism, and conservation. This approach enables coherence and synergy in contributing to the country's development goals.
6. **Regional collaboration:** Considering the links with neighbouring industries, provinces, and countries also looking at PtX development can promote regional collaboration and harmonization of standards and practices.

7. **Stakeholder engagement:** An SEA process would typically involve extensive consultations with various stakeholders, including local communities, non-governmental organisations (NGOs), industry players, and government agencies. This promotes participatory decision-making, stakeholder 'buy-in' and transparency; building trust and ensuring that stakeholder concerns are considered in the planning and development process.

11.1.2 Project-level guidance

Ecologically, South Africa is a megadiverse country with numerous unique species and ecosystems. It's social and economic systems are also diverse, with severe spatial and demographic inequalities in access to resources, making these systems fragile, and sensitive to stressors. 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. For this purpose, H2.SA developed an EIA guideline for South Africa aimed at those involved in PtX project EIAs, namely: EAPs, case officers and project developers.

11.2 Public acceptance of PtX projects

Public acceptance of a South African PtX economy and, by proxy, individual PtX project applications, will depend on the full or partial resolution of the following key issues:

1. **Policy clarity:** In any transformative initiative, policy clarity and implementation set the foundation, providing both industry players and the public with a view on the government's intentions. Further to existing policy guidance provided in the Hydrogen Society Roadmap (DSI, 2021) and Commercialisation Strategy (DTIC, 2022), updated policy briefs demonstrating the initial successes and milestones with actual implementation of projects, as outlined in the plans of the roadmap commercialisation strategy, will go a long way to building more trust and buy-in.
2. **Conflicts with REIPPP:** The Renewable Energy Independent Power Producer Procurement Programme (REIPPP) has been a cornerstone in advancing renewable energy, and energy security in South Africa. Any publicly perceived competition or contradiction between new PtX roll-out and current/future REIPPP projects could contribute toward scepticism. Demonstrating how PtX complements and aligns with the goals and implementation of REIPPP would be essential.
3. **Growth and jobs:** A significant determinant of public acceptance will be the tangible economic benefits a PtX economy can bring to South Africa. PtX could potentially be a significant revenue stream, boosting foreign exchange reserves and creating jobs. With clear policy direction, this revenue could then be reinvested in South Africa's domestic energy infrastructure, and programmes like the REIPPP. This argument is contingent on transparent and efficient use of revenues, something that requires robust governance.

4. **Institutional trust:** Trust in the institutions spearheading the PtX agenda is important. Past challenges with state-owned enterprises like Eskom have made the need for transparency and accountability even more critical. Efficient governance, openness about decision-making processes, and regular policy updates would be essential in enhancing the currently low level of public trust.
5. **Winners and losers:** Every major transition has beneficiaries and those who are adversely affected. In some instances, through the transition, win-win solutions will be possible, in others, win-lose outcomes are inevitable. The coal sector, for instance, might see job losses and major socio-economic shifts around mining towns. Being explicit about these challenges, mitigating these negative impacts where possible, and creating response pathways for those negatively affected, could reduce backlash and resistance.
6. **Sustainability advantages:** The sustainability risks and benefits of PtX need to be empirically examined against the status quo, across the full PtX production life cycle, and then clearly communicated to stakeholders through participatory, inclusive science-policy processes. This would include more research into the mechanisms of direct environmental and social impact (covered within the scope of this report), the macro and local socio-economic opportunities associated with different development scenarios, plus the life-cycle sustainability issues associated with GHGs (operations and transport) and downstream PtX use in South Africa (fertilizers and fuels).
7. **Human safety concerns:** There are substantial public apprehensions about the safety of manufacturing, storing, and transporting compressed gases and fuels. Assuaging these fears would require strict technical safety guidelines, regulatory oversight, and continuous monitoring. The regulatory framework for good safety is reasonably well established, but much depends on the institutional capacity to implement the regulations in a competent, trustworthy fashion.
8. **Community engagement:** Adopting a collaborative inclusive approach, ensures diverse perspectives shape the PtX roll-out, in ways considered to be broadly acceptable by those stakeholders affected. This can enhance the legitimacy of the policy programme, ensuring it's not seen as a top-down imposition, but rather a collective journey (USDOE, 2023).
9. **Community benefit plans:** Integrating community benefits into the core of PtX projects ensures they're not just commercially viable but also socially valuable and acceptable. This could mean prioritizing local hiring, investing in local infrastructure, or supporting community development initiatives (USDOE, 2023).
10. **Communication and media:** Effective communication is pivotal. This goes well beyond relaying information, to actively fostering a public discourse of understanding, highlighting benefits, addressing concerns, and building a shared vision. By ensuring that stakeholders have access to accurate and comprehensive information, their disposition towards PtX can shift positively (Vallejos-Romero et al., 2023).

11.3 Using a diversity of knowledge production practices

A wide diversity of actors and institutions are driving forward the prospect of a South African PtX economy, including government, research organisations, the private sector, and NGOs. Developing appropriate science-policy interfaces which act as intermediaries between different PtX actors and institutions is essential for both knowledge dissemination and realising an integrated vision of a sustainable energy economy. This could be undertaken through a range of science-policy processes (Table 10).

Table 12: Science-policy interfaces that can be used to share best practices and lessons learned in support of a sustainable PtX economy

Science-policy interface	Explanation
1) Virtual platforms	Tools, websites, maps, interactive portals where stakeholders can access the most up to date, integrated PtX-relevant knowledge (technical, financial and sustainability-related).
2) Science-policy mediators	Individual, renowned scientists or experts in the field of PtX, energy planning, policymaking, and the sustainability sciences.
3) Processes of knowledge production	Exploratory processes such as research programmes producing peer reviewed journal publications and/or other technical content for widespread public consumption.
4) Processes of knowledge synthesis	Open knowledge synthesis processes like SEA for a programme/policy-level view, or EIA for a project-level view to inform decision-making on specific projects.
5) Temporary think-tanks	Groups of technical experts. Relatively closed to the public and intellectually homogeneous. Used for specific technical advice on an ongoing basis to support roll-out of a PtX economy.
6) Permanent expert committees	Permanent body of technical and political experts, usually legislatively mandated group. Used for specific technical and political advice on an ongoing basis to support roll-out of a PtX economy.

To maximize the effectiveness of the proposed science-policy interfaces, it is vital to ensure they are interconnected rather than operating in isolated silos; for example, insights from temporary think-tanks should be integrated into knowledge synthesis processes and shared on virtual platforms. There is also a need for inclusivity in these frameworks, where even in more typically exclusive discussion forums, such as think-tanks, the broader stakeholder community, especially marginalized groups, should be given opportunities to both contribute and access vital information. Embedding regular feedback mechanisms will foster continuous improvement, and through capacity-building initiatives like training sessions, webinars, and workshops, stakeholders can be empowered to leverage these interfaces adeptly. If implemented and evaluated correctly, these interfaces can play a pivotal role in advancing South Africa's journey towards a sustainable PtX economy.

11.4 Suggestions for new research

South African policymakers, project developers and stakeholders lack an integrated vision of how large-scale PtX production will actually look on the ground. From a sustainability perspective, the major knowledge gap is uncertainty about the scope and scale of the physical footprints required to support PtX production around SEZs. A sustainable PtX economy strongly depends on being able to practice avoidance (top of the mitigation hierarchy) i.e., using spatial planning to avoid development in sensitive social and ecological systems. Presently, it is impossible to get a sense of the spatial requirements of PtX production, and how these requirements might conflict with existing or future land-uses. This could be remedied by developing PtX production scenarios using a South African SEZs as a case study. The scenarios would:

- Outline three PtX scenarios for the year 2035 for a case-study SEZ (no PtX, small PtX, big PtX);
- Describe the PtX products and quantify how much of each product might be made, across each scenario, for both export and domestic consumption;
- Working backwards from there, estimate the input requirements for each scenario (water via SWRO and electricity via RE) and calculate how these translate into spatial, infrastructural footprints in and around the SEZ;
- Consider the potential for offshore wind for electricity generation around SEZs like Coega and Richard's Bay owing to the significant terrestrial biodiversity impacts associated with onshore renewable energy production (especially land clearance for solar PV).

Top-down landscape vulnerability modelling would then be used to check degrees of fit between the quantified PtX scenarios, existing socio-ecological features, and future planned land-uses. The landscape modelling would include the following activities:

- Building a geographic information system (GIS) regional vulnerability model within and around a case study SEZ;
- Translating the quantified PtX scenarios (no PtX, small PtX, big PtX) into spatial footprints, across technology types;
- Cross checking spatial footprints of the PtX scenarios within the constraints of the regional vulnerability model and comment on the socio-ecological feasibility of the different scenarios.

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