South Africa's Water-Energy-Food Nexus in the context of Climate Change: A Research Agenda

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Acronyms and Abbreviations

AFD	Agence Française de Développement
BFT	Blended Finance Taskforce
CABLE	CSIRO Atmosphere-Biosphere Land Exchange Model
CCAM	Conformal Cubic Atmospheric Model
CPI	Consumer Price Index
CSIRO	Commonwealth Scientific and Industrial Research Organization
CST	Centre for Sustainability Transitions
DALLRD	Department of Agriculture, Land Reform and Rural Development
DBSA	Development Bank of South Africa
DoE	Department of Energy
DFFE	Department of Forestry, Fisheries and the Environment
DMRE	Department of Mineral Resources and Energy
DPWI	Department of Public Works and Infrastructure
DSS	Decision-Support-System
DWS	Department of Water and Sanitation
FABLE	Food, Agriculture, Biodiversity, Land-Use, and Energy
GCM	Global Climate Model
GDP	Gross domestic product
GHG	Greenhouse gas
HDI	Human development index
HW	Heat wave
IEA	International Energy Agency
IPBES	Inter-Governmental Panel on Biodiversity and Ecosystem Services
IPC	Integrated Food Security Phase Classification
IPCC	Governmental Panel on Climate Change
IRENA	International Renewable Energy Agency
IRP	International Resource Panel
JET	Just Energy Transition
JMP	Joint Monitoring Programme
JET IP	Just Energy Transition Investment Plan

MFA	Material flows analysis
MOU	Memorandum of understanding
NBI	National Business Initiative
NDC	Nationally Determined Contribution
NDP	National Development Plan
NERSA	National Energy Regulator of South Africa
NIP	National Infrastructure Plan
NPC	National Planning Commission
NT	National Treasury
PCC	Presidential Climate Commission
PECS	Programme for Ecosystem Change and Society (PECS
PIE	Political Industrial Ecology
PSG	Practical-social-governance
RCM	Regional climate models
SA	South Africa
SATIM	South African TIMES
SATIM-GE	SATIM model coupled to eSAGE
SA-TIED	Southern Africa – Towards Inclusive Economic Development
SDG	Sustainable Development Goals
StatsSA	Statistics South Africa
TORs	Terms of references
UNEP	United Nations Environment Programme
UCT	University of Cape Town
UNFCCC	United Nations Framework Convention on Climate Change
UNDS	United Nations Statistics Division
UM	Urban Metabolism
WCDM	Water Conservation and Demand Management
WEF	Water-energy-food
WEF CC	Water, Energy and Food in the context of Climate Change
Wits	University of the Witwatersrand

Introduction

Climate change, biodiversity loss and resource depletion are global realities that are having increasingly serious negative impacts on global and national economies. Three major global research initiatives provide the scientific focus for these global dynamics, namely the Inter-Governmental Panel on Climate Change (IPCC) for climate science (IPCC, 2022), the Inter-Governmental Panel on Biodiversity and Ecosystem Services (IPBES) for ecosystem science (IPBES, 2019), and the International Resource Panel (IRP) for material flow analysis (IRP, 2019). All three global dynamics analysed by these scientific bodies translate into practical challenges at the national level. The Water-Energy-Food nexus brings into focus where all three of these global dynamics intersect, with serious economic challenges.

Energy has traditionally been derived from fossil fuels extracted from the crust of the earth. This is a limited resource that is running out, and the combustion process relocates the CO^2 locked in sub-surface deposits into the atmosphere where it causes global warming with negative societal and economic consequences. Recently published scientific research shows that there are 16 earth-system tipping points that get activated at different intensities as warming proceeds through the 1.5-degree warming barrier, and beyond (McKay et al., 2022). Coal-fired power is also water-intensive. The transition to renewables is a transition from one set of non-renewable resources plus large quantities of water to another, namely to a combination of minerals and metals (especially rare earths) that will be required in greater quantities than if the economy remained dependent on fossil fuels (IRP, 2017). More copper, more steel, more rare earths and more cement will be needed compared to what will be required if the global economy remained dependent on fossil fuels. This has major implications for the mining industry, the structure of the power supply industry and everyday life (especially mobility, housing and food). South Africa has an ageing fleet of power stations, many of which need to close down over the next two decades. Funding to build new ones is unlikely, and renewables are now cheaper than the cost of running an existing coal-fired power plant and far cheaper than a new one. As South Africa's Energy Action Plan makes clear, there are now 30 GW of renewables in the pipeline arising from decisions made in 2022.

Water, on the other hand, is a scarce resource that is used inefficiently in South Africa. There are 5000 dams, 3800 of which are small farm or town dams. Underground water is scarce, and around 30% of all piped water is wasted due to leaks and other inefficiencies. Agriculture uses 61% of the water for food production, thus constraining what is available for urban consumption and expanding urban populations. South Africa produces enough food to feed all South Africans, and yet around 30% of South Africans are food insecure. This is partly due to gradual disintegration of the natural systems that food production depends on (i.e., soils, biodiversity and water supplies), but it is also due to the fact that the food system is geared for middle class consumers and exports and not the needs of the poorest sections of society.

Climate change has resulted in a global and South African commitment to Net Zero emissions by 2050. It is also a major threat to our future water supplies. Water resource consumption rates have generally tracked economic growth rates in South Africa, as have rates of fossil fuel-based energy consumption. If this continues without any decoupling, water resource constraints will join energy constraints as constraints on future economic growth (IRP, 2019). Climate change also drastically affects food supplies, in particular via negative impacts on water resources (surface and sub-surface), soil quality, land-use change and ecosystem changes.

It is clear that the water, energy and food systems need to change. The norm has been to manage these sectors independently, but research has revealed that these resources are interlinked in multiple, complex ways that may result in synergies and/or unintended consequences (Newell & Goldstein, 2019). The impact of climate change on these resources further exacerbates the challenge of managing them in a manner that ensures sustainability and resilience.

In response to these intersectoral challenges, the SA-TIED Phase II project has the workstream Water-Energy-Food in the context of Climate Change (WEF CC) which aims to answer the following overarching research questions: what system changes (policy, regulatory, institutional, financial) are required to ensure that South Africa has long-term sustainable supplies of energy, water and food in the face of climate change? What are the related investments required to achieve this? What are the long-term economic consequences of sustainable supplies of energy, water and food relative to a business-as-usual scenario?

Based on an understanding of the workings of the WEF nexus in particular contexts, strategic decisions can be derived and justified by evidence and the effect thereof measured. A deeper understanding of these resource flows could inform the appropriate policy and financial decisions that can lead to a more just transition in SA. In order to adequately address the research inquiry, the WEF CC research agenda is comprised of five focus areas which are more explicitly defined in their respective terms reference under Section 4. These focus areas are:

1. Climate modelling to determine the future climate change impacts on food, energy, and water systems.
2. Financial analysis of the investment requirements to achieve net zero by 2050.
3. Financial analysis of the investment requirements to achieve water security by 2050.
4. Land-use implications of future food needs in the face of urbanisation and population growth.
5. The need for a hybrid modelling approach that builds on SATIM-GE.

This research agenda paper is structured as follows: Section 2 follows after the introduction and will delve into the WEF nexus literature from which the project is derived, Section 3 will situate the WEF nexus within the South African context, Section 4 will provide summaries of the terms of references (TORs) for each of the five focus areas within the WEF CC project and Section 5 will conclude the agenda paper.

Overview of the WEF nexus literature

The emergence of the nexus debate

The WEF Nexus emerged as a framework for resource governance in response to the inadequacies of traditional approaches where resources are managed in isolation from one another (Weitz, Strambo, Kemp-Benedict & Nilsson, 2017; Newell, Goldstein & Foster, 2019). The problem with the traditional approaches to resource governance is that they do not account for trade-offs and cascading effects between resource systems and the systems within which they are embedded. By contrast, the WEF Nexus approach proposes a form of integrated resource governance where trade-offs are mitigated, vulnerabilities leveraged, and synergies maximised, simultaneously reinforcing the resilience of these systems in harmony with one another (Smajl, Ward, Pluschke, 2016; Weitz *et al.,* 2017; Newell et al., 2019). To achieve these outcomes, the WEF Nexus approach proposes systemic co-management of WEF systems and cross-boundary collaboration with coordinated resilience strategies in mind (Smajl *et al.,* 2016; Weitz et al., 2017; Newell *et al.,* 2019). For this reason, the WEF Nexus framework is represented as a supporting instrument for a green economy and resilient global development (Shlör e*t al.*, 2018)

Although the first WEF Nexus-related article was published in 1988 (Cohen & Allsop, 1988), the concept only appeared in the international arena in 2008, when the World Economic Forum called for a better understanding of the interconnections between water, energy and food (Smajgl *et al*., 2016). Since then, there has been a rapid increase in WEF Nexus publications, with 2016 alone seeing 213 publications of the total 1 399 publications identified in Newell *et al.'s* (2019) 44-year review of WEF Nexus literature.

A call for cooperation across sectors and scales

It was found that there was some uncertainty as to what precisely the term WEF Nexus represents (Urbinattii *et al*., 2020), with some authors arguing for a clearly defined concept to enable the identification of what is and what is not a WEF Nexus problem (Katz, Padowski, Golsdby, Brady and Hampton, 2020).

Other authors argue that the ambition to construct a clearly defined concept is unrealistic and unfounded given the complex and context-specific nature of interconnected resource governance, arguing for fluid conceptualisations depending on the context and the need to prevent the stunting of possible negative impacts (Märker, Venghaus & Hake, 2018). Researchers, however, need to move away from quarrels about abstract conceptual clarity and instead move towards an empirical analysis of application. This move is promoted by Smajgl e*t al.* (2016), who argue for moving from abstract considerations to practical application, and then empirical observation.

From a practical perspective, the WEF Nexus was identified at the Bonn 2011 Conference on the 'Water Energy and Food Security Nexus – Solutions for the Green Economy', as a tool within the sustainability solutions toolbox which could address the following key opportunities/challenges (Table 1).

Table 1: Key opportunities/challenges addressed by a nexus perspective.

Importance of a nexus perspective for the following resource security and sustainability opportunities/challenges:	
Increased productivity and efficiency of resources	Decoupling economic development from resource use (Hoff, 2011; Martin-Nagle et al., 2012).
Waste as a resource in multi-use systems	Cross-sectoral management can turn waste and by-products into resources for other products and services, boosting overall resource use efficiency (Hoff, 2011).
Stimulating development through economic incentives	Economic instruments8 are required to stimulate investment towards innovations that help improve resource use efficiency9 (Hoff, 2011).
Governance, institutions and policy coherence	Multi-level governance and collective action require enabling conditions for horizontal and vertical policy coherence10 (Hoff, 2011).
Benefiting from productive ecosystems	A nexus perspective provides opportunities for improved ecosystem investment and

	management, a critical task given our dependence on these ecosystem services (Hoff, 2011).
Accelerating access (integrated poverty alleviation and green growth)	By sustaining our ecosystem services via a nexus approach, we are, in effect, maintaining our life support system. People experiencing poverty depend on these ecosystem services most directly, making it crucial to accelerate access to resources and sustain their functioning in a coordinated way (Hoff, 2011).
Capacity-building and awareness raising	With a cross-sectoral approach comes increased complexity, which needs to be addressed via social learning and capacity building11 (Hoff, 2011; Martin-Nagle et al., 2012).
Towards a Green Economy	Nexus can assist in creating an economy that results in improved social equity and human well-being while significantly reducing ecological scarcities and environmental risks (Hoff, 2011).

(Adapted from Hoff, 2011; Martin-Nagle et al., 2012)

From the opportunities/challenges identified in Table 1, a possible understanding of the WEF Nexus framework emerges (Martin-Nagle *et al*., 2012:25):

> A nexus perspective increases the understanding of the interdependencies across the water, energy, food and other policies such as climate and biodiversity. The nexus perspective thus helps to move beyond silos and ivory towers that preclude interdisciplinary solutions. It opens the eyes to mutually beneficial responses and the potential of cooperation. We must think and act interlinked to realise direct and indirect synergy potentials.

It is a call for cross-sector cooperation (water, energy, food), cooperation across multiple levels of state (national, provincial, local), cross-domain cooperation (public, private, and civil society), as well as transdisciplinary thinking (Martin-Nagle *et al*., 2012). The WEF Nexus is, therefore, a concept that extends further than just water, energy and food and encompasses a form of governance that can be described as integrated resource governance. Although this is the preferred outcome, it is found that many WEF Nexus studies were sector-specific, not concerned with all levels of state (national, provincial, local), and not focused on all cross-domain actors (public, private, and civil society) (Foley et. al., 2005; Newell *et al*., 2019; Mguni & van Vliet, 2021).

Cooperation: collaboration versus holistic integration

The WEF Nexus literature clearly calls for better cooperation for the goal of integrated resource governance. What needs to be clarified is how this cooperation can and should manifest, as well as the techniques, tools and frameworks required to make the proposed forms of governance practically viable. This would shift the debate from conceptual refinement to the practicalities of flexible governance, from structural idealisation to practical possibility. Should cooperation come from fully integrated governance units into single WEF Nexus departments, or should autonomous units be strongly linked towards better collaboration? These different proposed forms of governance - collaborations vs integration - represent two possible understandings of the WEF Nexus and how its call for cross-sector cooperation can and should manifest. Some authors who have given this question serious consideration include Smajgl *et al*. (2016), Weitz *et al*. (2017), Märker *et al*. (2018) & Urbinatti *et al*. (2020)

Smajgl *et al*. (2016:538) introduce a “sectorally balanced, dynamic nexus framework” in which sectors are equally weighted when grappling with relationships and ripple effects of governance decisions. The Dynamic Nexus Framework, as it will be referred to from here on, is illustrated in Figure 2.1.

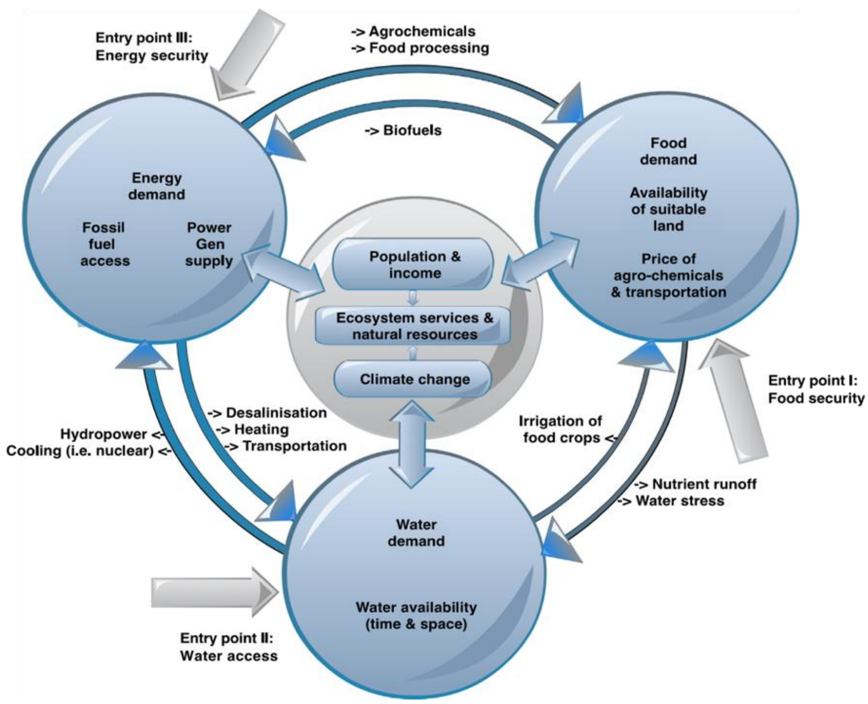

Figure 2.1. Dynamic Nexus Framework

(Source: Smajgl *et al.*, 2018:535)

In contrast to this would be a traditional static-comparative and partial approach which gives unequal consideration to a specific sector while comparing states before and after the change. Instead, the Dynamic Nexus Approach emphasises the constant interaction between "the three sectors, and between the Nexus core and the three Nexus sectors" (Smajgl *et al.*, 2018:535). The Nexus core refers to drivers, such as population growth and climate change, that simultaneously influence water, energy, and food dynamics, thus resulting in cross-sector feedback (Smagjl *et al*., 2016). Smajgl *et al*. (2016) tested the practical effectiveness of a Dynamic Nexus Framework in the transboundary context of the Mekong Basin. They found that it produces novel insights for cross-sectoral dynamics, as it "revealed how the occurrence, valency and magnitude of sectoral connections emerge and are altered as a consequence of single sector interventions in a water–food–energy Nexus" (Smajgl *et al*., 2016:532)

Weitz *et al.* (2017), Märker e*t al.* (2018), and Urbinatti e*t al.* (2020), however, caution against a framework that argues for the idea of full integration of sectors into one system as their research suggests this approach can lead to collaborative inertia. This is a crucial point to consider when it comes to generating the adaptive capacity needed when governing resilience, as cross-scale coordination is needed without paralysing the ability to be adaptive and creative — a factor that, in many ways, is determined by diversity and flexibility (Biggs e*t al.*, 2015; Wagenaar & Wilkinson, 2015).

Märker e*t al.* (2018) specifically uses a governance, policy and institutional approach to approach their proposed form of WEF Nexus integrations. This is very much the same as Weitz e*t al.* (2017), and Urbinatti e*t al.* (2020), who realise the WEF Nexus structural debate is essentially a debate about governance, the enactment of which will rely on policy and institutional transformation according to the best form of integration/collaboration. Urbinatti e*t al. (*2020) highlight the benefits and disadvantages of perceived governance integration (sector and scale) by stressing that rigid integration may be disadvantageous; instead, they promote flexible governance arrangements. This point is also raised by Weitz e*t al.* (2017), who propose the importance of neutral spaces rather than the formal merging of sectors.

Märker e*t al. (*2018) are, however, the only ones to practically explore these propositions. This is done by exploring possible pathways for achieving an integrated WEF Nexus governance framework and highlighting problems with institutional change and policy integration. This information is then used by Märker et *al.* (2018) to develop and practically explore two possible conceptual WEF Nexus frameworks.

This first, represented by Figure 2.2, is known as the Holistic WEF Nexus Integration Framework, which describes a horizontal policy integration framework that defines the WEF Nexus as a single, fully integrated system.

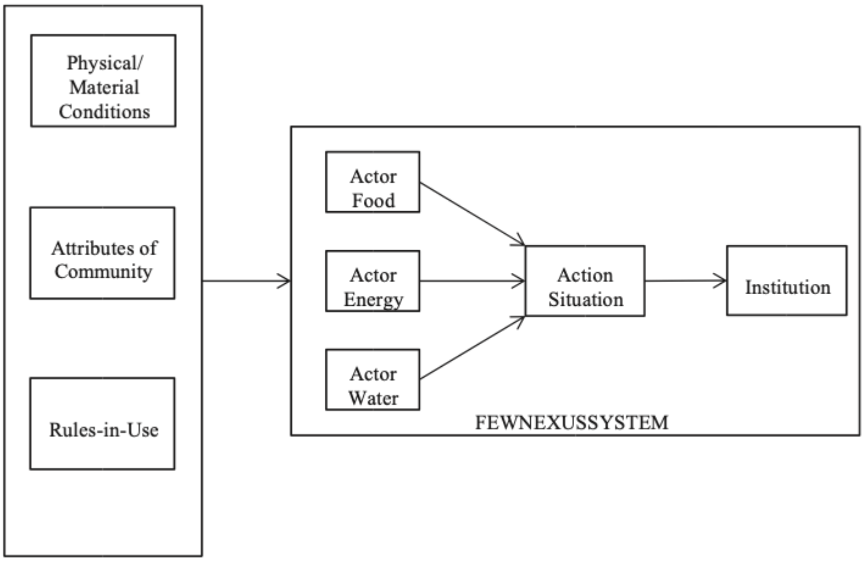

Figure 2.2 Holistic WEF Nexus Integration Framework

(Source: Märker et al., 2018:294).

The second, illustrated in Figure 2.3, is known as the Collaborative WEF Nexus Framework, and describes a vertical policy integration framework primarily based on existing structures and the reframing of the current institutional setting towards more collaboration.

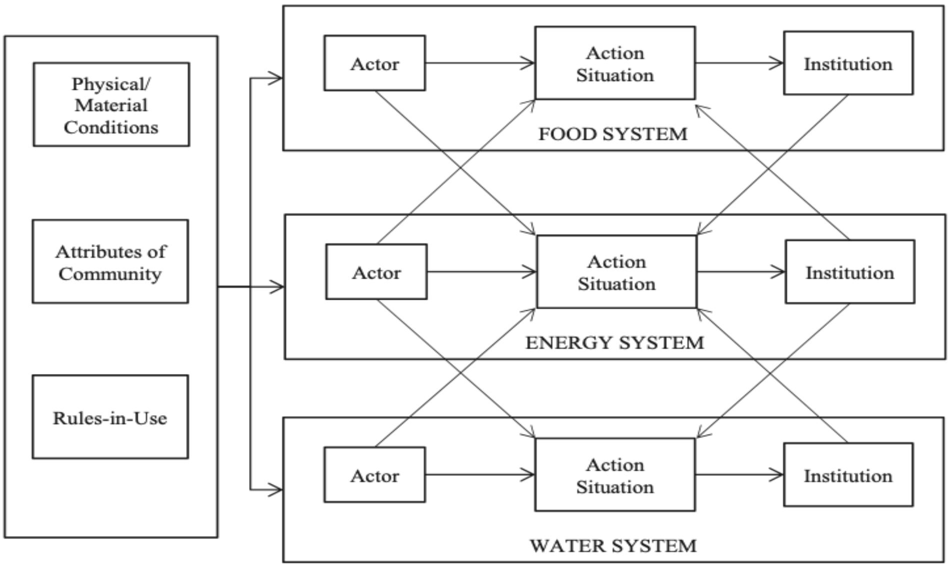

Figure 2.3 Collaborative WEF Nexus Framework

(Source: Märker et al., 2018:295).

After developing these two theoretical frameworks, Märker e*t al.*, 2018 tested both for strengths and weaknesses in governing the WEF Nexus using two cases of integrated governance in Germany: The

German Sustainable Development Strategy (GSDS) 2016 and Section 90 of the Renewable Energy Sources Act.

The GSDS 2016 had been developed by the German Federal Government in response to the call for coherent, holistic policy frameworks that could address each of the UN's Sustainable Development Goals (SDGs), as well as the cross-references and interconnections between the 17 SDGs, including those directly and indirectly related to the nexus sectors (Märker e*t al.,* 2018). The development of GSDS 2016 was governed by the State Secretaries' Committee for Sustainable Development (StsA). It consists of representatives from each of the 14 federal ministries and is directly connected to the Federal Chancellery (Märker e*t al.,* 2018). Therefore, the StsA constitutes a central authority responsible for a holistic strategy while being located on a supra-sectoral level, hence showing a high level of horizontal policy integration. As Märker et *al.,* (2018: 296) write:

> "The 2016 GSDS provides an overarching strategy endorsed by a strong authority on a supra-sectoral level and influenced by a broad variety of different actors. It formulates specific targets and measures for the FEW nexus sectors and accounts for interconnections between them. In this sense, the 2016 GSDS serves as a valid example of horizontal policy integration using the holistic FEW nexus framework."

The GSDS 2016 is, however, not without shortcomings, as it recommends a restructuring of the institutional setting, while evidence suggests that institutional settings usually do not change as fast as resource problems need to be solved (Märker e*t al.,* 2018). The strategy is therefore of great importance for actual policy integration, yet a strategy alone is simply as effective as the competences of the central authority who must endorse it.

There are, however, alternative instruments of policy integration, such as Germany's Section 90 of the Renewable Energy Sources Act, which represent vertical dimensions of integration and thus the second WEF Nexus Framework. The Renewable Energy Sources Act (EEG) represents the most important instrument for achieving renewable energy sources targets in Germany. This is because the EEG fixes a feed-in tariff specific to respective energy sources while ensuring feed-in priority for electricity generated from renewable sources (Märker e*t al.,* 2018). This includes the use of Biomass, which can have a significant impact on land use, ecosystem services and biodiversity (Märker e*t al.,* 2018). This makes the case of bioenergy a prominent nexus example, as it simultaneously addresses water, energy and agricultural concerns (Märker e*t al.,* 2018).

Section 90 of the EEG regulates the rules for setting up sustainability criteria (such as sustainable cultivation and production and reduction of GHG emissions) which needs to be met by producers to receive subsidies for the use of biomass as a source of electricity (Märker e*t al.,* 2018). These criteria are however not defined by EEG itself. Instead EEG authorises the Federal Ministry for the Environment, Nature Conservation and Nuclear Safety (BMU) in accordance with the Federal Ministry for Economic Affairs and Climate Action of Germany (BMWi) and the Federal Ministry of Food and Agriculture (BMEL) to choose the requirements and rules laid out in the Biomass-Electricity-Sustainability Ordinance (BioSt-NachV), while the BioSt-NachV simultaneously strives to implement the EU Renewable Energy Directive (which has the role of directing the federal ministries to bind certain compensation payments to specific environmental and sustainable standards).

This example of vertical policy integration is described by Märker e*t al.*, (2018: 297) who write:

> "Using IAD framework terms, the EEG and the EU Renewable Energy Directive represent formal rules that are clearly assigned to the energy sector. However, in terms of criteria for the sustainable and environmental-friendly cultivation of biomass, BMU acts as the main actor, involving BMEL and BMWi in the action situation. The institutional outcomes of this action situation are specific sustainability requirements defined in the BioSt-NachV."

It is therefore indicative of a case study example of vertical policy integration among WEF nexus sectors because it is situated on a specific sectoral level which incorporates and draws together procedures that can lead to coherent policy outcome (Märker e*t al.,* 2018). Some potential shortcomings may emerge due to insufficient monitorisation, communication and shared information, making it of critical importance for these factors to be considered when implementing a form of vertical policy integration. Despite these potential shortcomings, Märker e*t al.* (2018: 297) argue that by constantly adjusting and evolving the EEG, the "Federal Government uses and strengthens an existing institution to achieve overarching climate and energy targets without reconsidering basic structures", making it an excellent case study of the success that can come from vertical policy integration.

After analysis of the results, Märker et *al.* (2018) conclude that effective WEF Nexus governance requires aspects of both policy integration options depending on the context. As they write:

> "Since vertical policy integration requires lower levels of learning, it is easier to achieve. It builds on existing institutions and increases cooperation and is assumed to have a higher impact on policy implementation. However, regarding the overarching goal of sustainable development, it must be questioned whether various nexus-smart sector policies alone would equate to a practical governance concept for sustainable development." (Märker e*t al.*, 2018:297).

Key Learnings

What then emerges from these various debates? Smajgl *et al*. (2016) bring forward the workings of a dynamic and sectorally balanced nexus perspective. Although Weitz *et al.* (2017), Märker *et al.* (2018), and Urbinatti *et al.* (2020) agree with Smajgl *et al*. (2016) in that a dynamic, nested perspective is required, they caution against perspectives where sectors are balanced in a manner that turns them into a single sector (although this may be necessary at times). Further suggestions are made by Al-Saidi and Elagib (2016), who argue that one must consider a prism-view of one sector that takes links to the other two sectors, much like the nested view proposed by Smajgl *et al*. (2016).

In conclusion, these various arguments collectively suggest that a collaborative, dynamic WEF Nexus framework is required, which uses a nested view/prism view but not full sector integration — although this can be beneficial in specific contexts. It is, therefore, clear that although these are crucial considerations when setting up WEF Nexus cooperation in practice, context is vital. Conceptual clarity needs to emerge from the analysis of practical WEF Nexus governance applications in different contexts.

Analytical capacity as a catalyst for cooperation and coordination

The literature clarifies that although structural manifestation is context-specific, analytical capacity is necessary for any WEF Nexus approach (Hoff, 2011). What is meant by analytical capacity is a means of analysis which can capture complex system component interactions, ripples and reactions using integrated assessment of water, energy and food at all scales, enabling quantitative trade-off analyses and better decision-making (Smajgl *et al.,* 2016; Newell *et al*., 2019). One proposed way to do this is with concepts, perspectives, and analytical tools emerging from the field of Urban Metabolism (UM) — an area used to explain the physical material flows analysis (MFA) of resources through urban systems (Newell *et al*., 2019).

To illustrate this approach, it is worth discussing the example of such an analytically supported decision support system based on MFA that can be found at the V&A Waterfront in Cape Town, South Africa (Swart, 2023). V&A Management decided to use a tool called GCX DASH that was developed by a Cape Town-based technical solutions company. It is an analytical tool that tracks the physical material flow of shared resources throughout the V&A Waterfront. Although it currently only tracks water, energy and waste, it still makes for an ideal case study of a Decision-Support-System (DSS) based on material flow analysis (MFA) throughout an urban metabolism (UM) which is, in this case, a precinct/neighbourhood known as the V&A Waterfront.

However, this quantitative MFA must be paired with qualitative perspectives, such as governance, socio-economic and political considerations (Foran, 2015; Newell *et al*., 2019). This is especially the case concerning the WEF Nexus, as interdisciplinarity needs to be at the core of a field that proposes cross-sectoral cooperation (Foran, 2015, Berman, Shwom & Cuite, 2019; Newell *et al*., 2019). Some suggestions are made by Newell *et al*. (2019), who propose a merger between industrial ecology's quantitative UM approach with qualitative socio-political considerations to form a new kind of analysis referred to as Political Industrial Ecology (PIE).

In contributing to this mixed method approach, research was conducted at the V&A Waterfront by investigating the quantitative MFA-based DSS (GCX DASH-) through a practical-social-governance (PSG) perspective (Swart, 2023).

V&A Waterfront Case Study

Decoupled Resource Use via data-based Resource Governance

The use of GCX DASH enables the V&A Waterfront to enact a measure of decoupled resource governance. Decoupled resource governance means sustaining economic growth at a certain percentage while your dependence on resources goes flat or declines (UNEP, 2011). By using GCX DASH, the V&A Waterfront has largely decoupled a precinct's economic and financial growth from the growth in carbon emissions, water, waste, and energy. Since practical examples of decoupled resource governance using a DSS are expressed in the literature as virtually non-existent, the V&A Waterfront presents a significant example on a global level.

A practical governance result that emerged from the use of GCX DASH- was the ability to save time. What would usually be a time-consuming and expensive yearly black box carbon disclosure exercise became an automated updated real-time analysis of consolidated resource data and related carbon emissions data (Swart, 2023). This not only saved the V&A Waterfront time and money, but it offered them a birds-eye view of data displayed on a live online accessible dashboard as well as a monthly

Eco-Analytics Report (Swart, 2023). The company responsible for GCX DASH- is GCX, a sustainability solutions company that has had a contract with the V&A Waterfront since 2018.

Projecting potential outcomes: better decision-making (CAPEX)

It is the bird's eye view of resource flows and patterns that allows the V&A Waterfront to know precisely what resources are being used on a monthly and yearly basis, in turn enabling them to make better decisions, as well as to set realistic sustainability-oriented performance targets for the year ahead (Swart. 2023). These annual targets are improvements on the previous year's performance following a standardised set of metrics (e.g., emissions, water use per person, waste per person, energy use, etc.). These targets are not, therefore, wishful thinking targets designed for political performance that can be construed as greenwashing. They are rooted in reality and are realistic and achievable. The system, therefore, enables a deep level of learning that enables better decision-making and the better setting of realistic targets.

The dashboard also makes it possible to project potential outcomes over time, for example, in 2030, 2040 or 2050, if the rate of improvement is maintained. In the case of the V&A Waterfront, this projection drives their CAPEX budgeting. Evidence suggests that with accurate key performance indicators (KPIs) and dynamic baselines, the V&A Waterfront has been able to compare buildings per square metre, enabling them to assess the performance of outliers while finding reasons for why these are outliers.

Previously (before GCX DASH-), CAPEX used to be "...driven by who shouted the loudest" (Swart, 2021). However, with the analytics tool in place, guided decisions directing CAPEX have been made that contribute ecologically and socially. As GCX 1(2022) explains: "You will be able to use data to identify where capital expenditure is required. So, yes, the dashboard does have the ability to indicate where it's required." This leads V&A 1 (2021) to describe the resource data flows enabled by GCX DASH- as "game-changing."

Unintended Consequences & Nexus thinking

The accurate measurement of waste throughout the V&A Waterfront enables better decision-making surrounding waste. One such instance occurred when using waste data: the V&A Waterfront management realised they could only go up to 43% landfill diversion as going higher leads to a hefty gate fee at landfills (V&A 2, 2022). This means they are essentially paying more than they are saving for recycling high quantities, an unintended consequence that GCX DASH picked up since it displayed environmental data in relation to financial data, otherwise known as materiality. As V&A 1 (2021) states, "We've proven with the platform that anything above 43% doesn't pay me to recycle", once again highlighting the importance of picking up materiality rather than pure non-financial data in isolation.

Realising these unintended consequences of recycling led the V&A management to seek alternative ways of dealing with waste. This is because the final assessment led to the approval of plans for a waste-to-energy plant using advanced pyrolysis treatment where all waste except glass and metal would go into the plant to make energy. In other words, the V&A Waterfront would stop effectively recycling on-site, as everything would be utilised for energy in the long run (V&A 2, 2022). Access to a complete data record of the V&A's MFA (provided by GCX Dash-) enabled them to use nexus thinking regarding water, energy and waste. As V&A 2 (2022) explains:

> Once we did the viability for the waste-to-energy, we knew that the amount of energy that we would be able to get from the waste-to-energy plant would be able to provide at least two-thirds of the energy required for the desalination plant. And the other third of that would be coming from the PV installations. So, it was kind of like a no-brainer for us. Because your payback period was within reach of what we were hoping for. And at least from a development perspective, we're not putting additional strain on the system, it would be able to generate our own electricity, which is great.

This indicates an example of how the GCX DASH- allowed for decision-making that takes a nexus perspective: a single intervention was constructed that would have reverberating effects on three distinct resources, namely waste, energy, and water. Other proposed interventions stemming from solutions assessment via the dashboard include commissioning a blackwater treatment plant to help the V&A deal with their wastewater (V&A 3, 2022). The blackwater treatment plant is being constructed at the site of the V&A Waterfront's current sewage pump station and will, once completed, treat sewage water to a level two standard, making it safe to use for irrigation. The option is there to upgrade the blackwater treatment plant to level one standard, making the treated water safe for consumption, however, this will only occur after a trial period.

In short, the GCX dashboard has allowed for the enactment of circular thinking as it made the V&A Waterfront aware that they have reached a ceiling regarding many of the systems meant to save and recycle resources. Significantly, MFA data underpinned this decision which, in turn, allowed for the proper nexus perspective to be possible and is thus a determining factor in enacting accurate nexus thinking.

Green leases & shared value ecosystem.

Another finding was the positive effects GCX DASH- had on the collaboration between tenants and landlords through supporting and reinforcing the enactment of green leases and a shared value ecosystem approach adopted at the V&A Waterfront. Green leases are essentially contracts between Growthpoint (including the V&A Waterfront) as landlord and their tenants, whereby they share the benefits and the expenses of driving efficiencies in water, energy, and waste (V&A Waterfront, 2022a). The shard value perspective refers to striving towards business outcomes that extend beyond just benefits for the shareholders and take a Social-Ecological Systems (SES) view in striving for holistic systems outcomes (V&A 1, 2021). With GCX DASH- in place, the V&A Waterfront can support both these agendas with accurate and up-to-date resource flow data displayed with excellent detail (for instance, they can show a specific tenant's consumption or a particular room within the tenant's building). This also helps with conflict resolution, as disputes can be resolved with accurate data (V&A 2, 2021)

Driving systems change: implications during Day Zero

The enactment of green leases and a shared value ecosystem are catalysts for systems change, and an example can be taken from the water crisis in Cape Town (Day-Zero) (Shepherd, 2019). Because the V&A relies on tenants for their total consumption, it was paramount to drive down consumption. During the water crisis, the way to get tenants to participate was to get all the significant users together in a room and to show comparisons in consumption rates using the GCX DASH- while also highlighting who the significant users were (V&A 1, 2021). By offering the data, the V&A Waterfront got these large consumers to ask questions, eventually driving their changes. Realising how much money their competitors save (made possible by showing the materiality of water consumption) incentivised the changes over time for many of these tenants.

Power dynamics: relationships of trust for the goal of systems change

Investigating how the implementation of GCX influenced the relationships between landlord and tenants leads to the logical conclusion that a DSS such as the GCX Dash enables shared information which is, in turn, critical in shaping the required relationships of trust needed to bring top-down and bottom-up governance structures into mutual relations. It is therefore argued that a shared DSS that tracks performances and stimulates better collective decision-making may be a part of the answer when it comes to shaping power dynamics via better connections to enable real, achievable systems change.

Water, energy and food in South Africa

The WEF Nexus presents a promising opportunity in addressing resource concerns but also represents a systems-based approach to governance in pursuit of the SDGs. In setting the research agenda, the following section provides a brief overview of South Africa's national resource landscape to contextualize the current resource dynamics.

State of Water in SA – overview

South Africa (SA) is considered a semi-arid country and ranked the 30th driest country globally (GreenCape, 2022a). As a result of increasing temperatures, the country is expected to experience more extreme weather events, particularly flooding and droughts which will affect water supply (Department of Water, 2022) thus increasing vulnerability to water shortages (GreenCape, 2022b). Between 2016 and 2021 (with the exception of 2018), the national storage of water has been noted to be below the national average (Department of Water, 2022). This is following a drought in 2015 which severely reduced national dam levels and exposed water system vulnerabilities (Donnenfeld, Crookes & Hedden, 2018).

Coupled to water scarcity, an uneven rainfall distribution and varying microclimates are characteristic of the region. As a result, summer rainfall is experienced in the eastern and central locations, winter rainfall in the western and south-western regions and all-year-rainfall in the remaining regions are shifting (GreenCape, 2022a) – see Figure 3.1. Roffe, Fitchett & Curtis (2021) highlight that climate research in SA focuses primarily on annual rainfall volumes, but not much on the changes in the timing of rainfall. They elaborate as this has negatively cascading impacts on crop yields and surface water supplies, which warrant more attention.

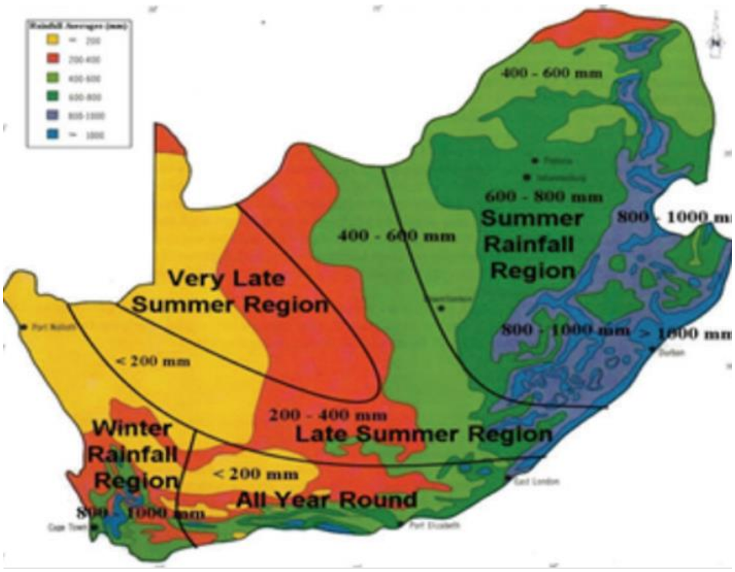

Figure 3.1: National rainfall distributions

(Source: Department of Water, 2022)

The Department of Water and Sanitation (DWS) is the centrally managed and mandated custodian of the nation's water resources, responsible for the management of resources and implementation of national policy. Water is delivered to users via a well-developed infrastructural system, predominately by means of the 5569 rain-fed dams across the country (Department of Water, 2022). But, maintenance on existing infrastructure and asset renewal is currently experiencing a backlog of R36bn, where R12.5bn is required for refurbishment due to inadequate maintenance and R23bn required for renewal of dated infrastructure (Department of Water, 2022). This presents challenges as agriculture, which contributes 3% to GDP (relatively small but sustains livelihoods and supports national food security), consumes 61% of the national supply followed by 27% for municipalities with mixed uses (residential, commercial and industrial) cannot function without this supply (GreenCape, 2022a). Moreover, this impacts strategic users, most notably being Eskom and SASOL, who are reliant on supply according to contractual arrangements but also represent the energy sector which consumes 2% of national supply. If compromised, energy and fuel shortages are likely to result (Department of Water, 2022).

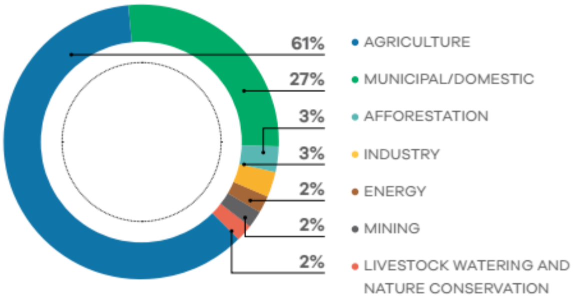

Figure 3.2: Water use in SA

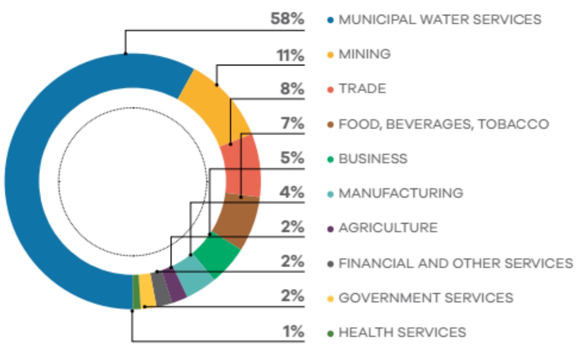

Figure 3.3: Financial contribution of each sector

(source: GreenCape, 2022a as cited in Department of Water and Sanitation, 2019)

Despite the climate and demand profile, national consumption per capita is 34% higher when compared to international benchmarks (235l/day vs 175l/d) (Department of Water and Sanitation, 2019). Moreover, it is predicted that demand will exceed supply by 10% by 2030 (Department of Water and Sanitation, 2019) driven primarily by ineffective tariff structures, inefficient use and wastage, and aging infrastructure underpinned by increased urbanisation, rising incomes and increased access to piped water (Donnenfeld, Crookes & Hedden, 2018). Even so, universal access to potable water is still not a reality for many. The 2021 StatsSA General Household Survey indicates that 45.2% of household had access to piped water in their homes, 29.4% had on-site water access, 12.2% accessed water via communal tap, 1.9% obtained water from neighbours while 2.7% still relied on water collected from river, streams, springs, stagnant pools and dams (Republic of South Africa, 2022).

Analysis of the future water balance shows that with supply augmentation efforts (which must be diversified (GreenCape, 2022a)) and efficiency measures, the gap between the 2030 supply and demand can be considerably narrowed (Department of Water and Sanitation, 2019). An independent report commissioned by the World Resources Institute (WRI) 2015 indicates that South Africa will experience severe water stress by 2030 which is worsened by 2040 under current usage trajectories (Luo, Young & Reig, 2015) – see Figure 3.. Water security is central in supporting economic recovery and development (GreenCape, 2022a).

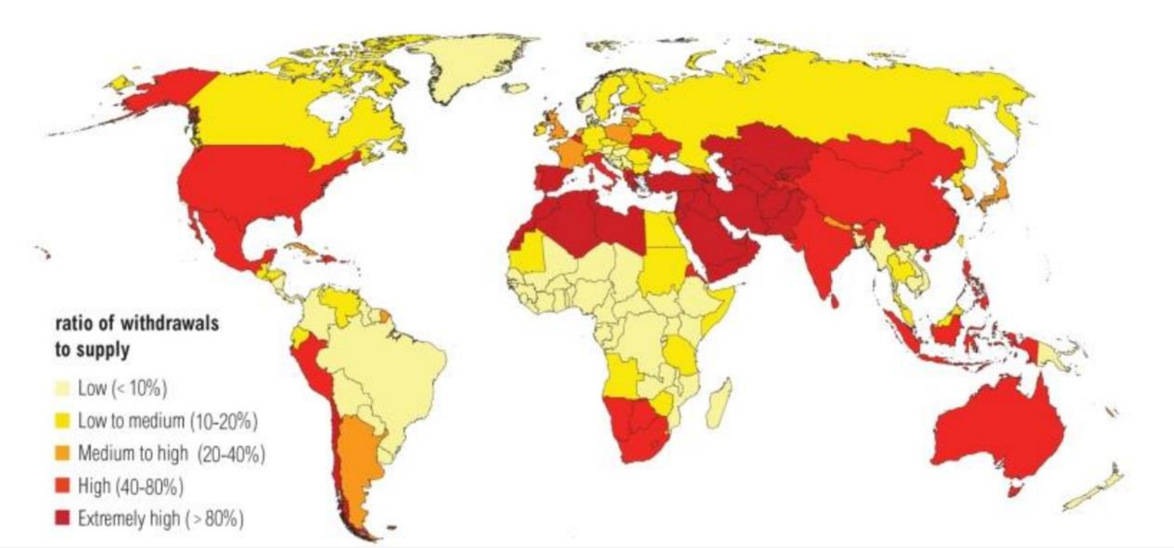

Figure 3.4: Water Stress by Country: 2040

(Source: *Luo, Young & Reig, 2015)*

Key levers for development in the water sector have been identified as: supporting resilience to the impacts of drought events, pursuing water security linked to economic development and improving access to water (GreenCape, 2022a)

State of Energy in SA – overview

South Africa's energy[1] sector is under the centralised control of the Department of Mineral Resources and Energy (DMRE), while the Department of Public Enterprises oversees the state-owned power utility – Eskom – that is responsible for the generation, transmission, distribution and sale of electricity. The National Energy Regulator of South Africa (NERSA) is responsible for regulating energy entities and granting licences.

Eskom supplies 90% of the nation's energy requirements, of which 85% is provided from coal-fired power stations (Eskom, 2022a). Figure 3.5 depicts the location of power stations, most of which are concentrated in the north-east, in proximity to coal reserves.

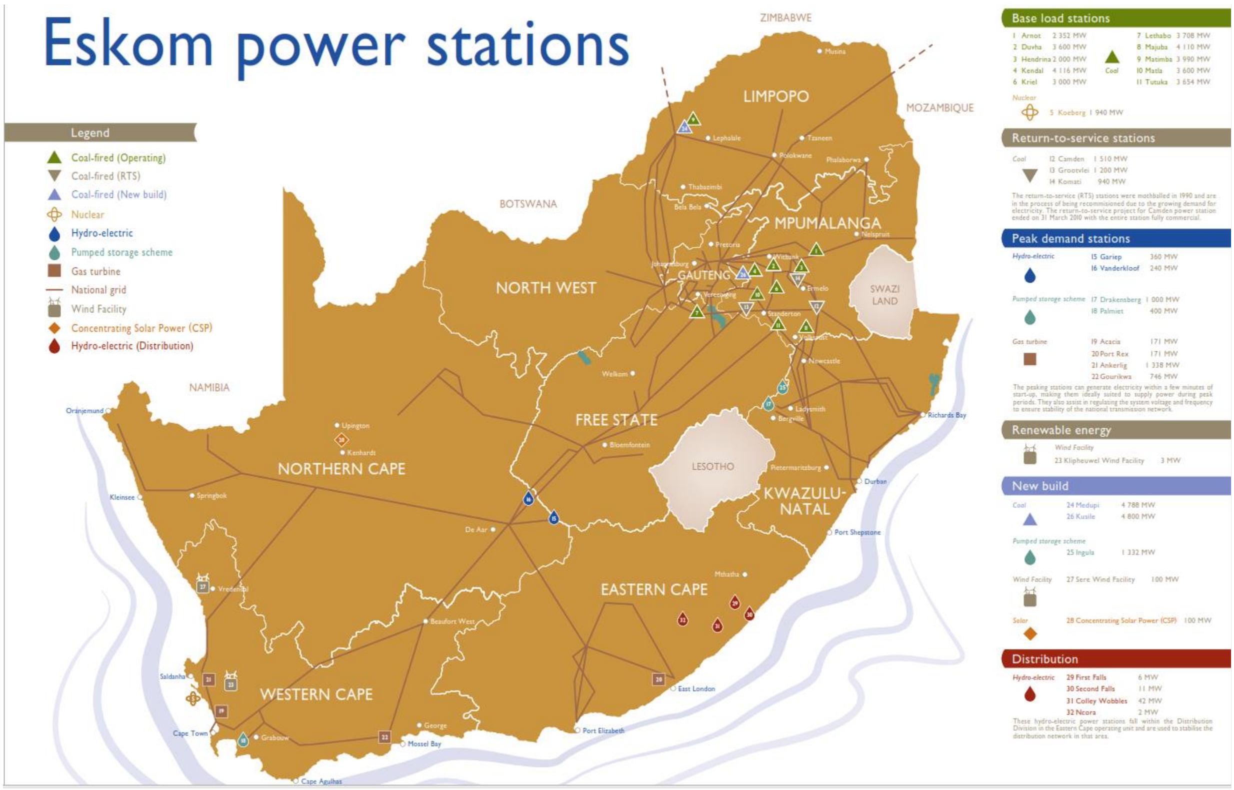

Figure 3.5 Eskom's national power plant footprint

(Source: Eskom, 2021b)

The role of Eskom as the monopoly electricity supplier is a point of strong contestation as load-shedding, implemented initially in 2007, is worsening to date and has detrimental effects on economic productivity. This is said to be due to rampant corruption plaguing the enterprise compounded with failure to maintain the generation fleet. Recent estimates by the South African Reserve Bank places the cost of load shedding (in terms of lost revenue) at R204 million per day at stage 3 and R899 million per day at stage 6 (News24, 2023) with another source estimating that prolonged stage 6 load shedding has a daily cost of R4 billion (Dumisa, 2023). 250 days of load shedding is predicted for 2023 (increasing from just over 200 days in 2022), equating to an estimated loss to the economy of R230 billion. This has massive implications for economic growth – owing to the inherent links between

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[1] For the purposes of this report, 'energy' will only comprise of electricity and will exclude other considerations such as fuels.

energy and the economy, but the effects may be even longer term as the subdued economic growth makes the country an unattractive investment destination.

Policymakers and practitioners are widely aware of the direct links between economic development and energy supply. Despite initial intentions to provide universal energy access by 2012, the government was unable to meet this target due to generation constraints, increasing urbanisation and growing demand (Sustainable Energy Africa, 2014). A new target to achieve universal access by 2025 was set by the Department of Energy (DoE, which was succeeded by the DMRE) detailed in the Electrification Roadmap (Department of Public Enterprise, 2019). Despite this, many South Africans remain energy poor – without access to the electricity grid and reliant on traditional energy sources (such as wood) (Guild & Shackleton, 2018) or having access but unable to afford electricity (Ye, Koch & Zhang, 2018).

> "Economic growth is an essential prerequisite for overcoming poverty. No country has achieved sustained economic growth without improving access to cleaner and modern forms of energy and the services that they provide. It is also globally recognized – based on the experiences of most industrial countries – that policies to "share" the benefits of growth are needed to address inequality and combat poverty. Energy services to support economic growth and energy policies to combat inequality in human welfare are thus both critically important." (Karekezi et al., 2012, p.158)

The Energy Progress Report indicates that 84% of South Africa's population has access to electricity (IEA et al., 2022) – see Figure 3.6. Access to electricity is a central component of socio-economic development and the eradication of poverty and may address structural unemployment (Department of Energy, 2009).

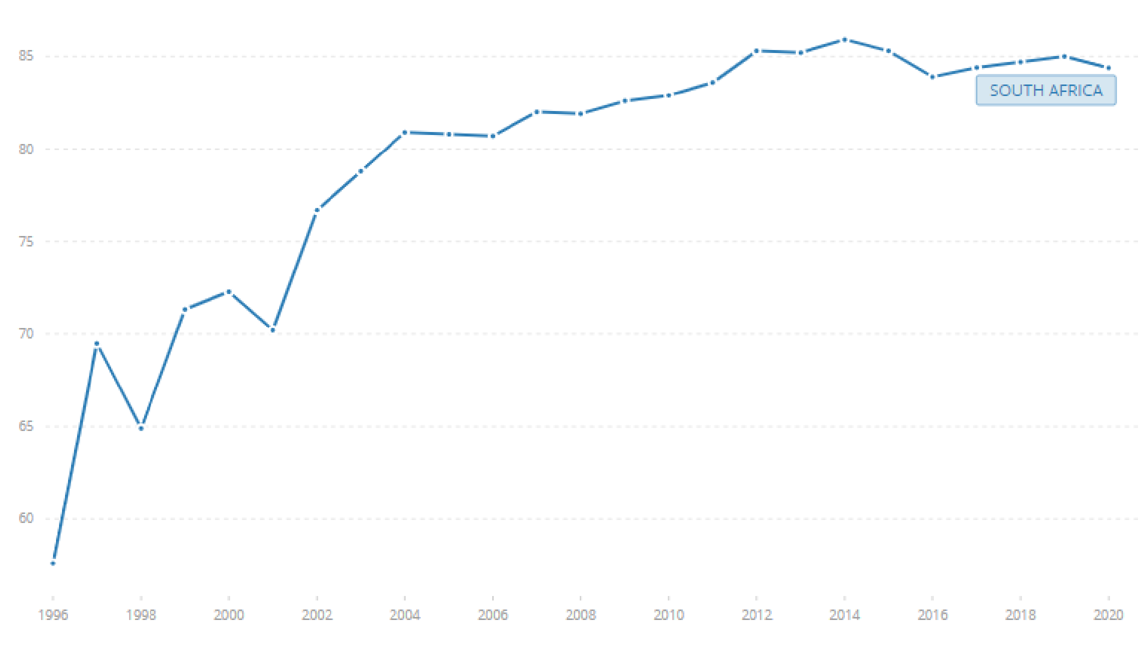

Figure 3.6: Access to electricity (% of population)

(Source: The World Bank, 2020)

In 2021, electricity generation produced 207.6 million tons of CO^2, with emissions related to the transport of coal to power stations accounting for 10% of that figure (Eskom, 2021b). Although somewhat dated, this places South Africa 15th in global CO^2 emissions, yet, on par with China in terms of CO^2 intensity per capita (WorldOMeter, 2016). The Nationally Determined Contribution (NDC) under the Paris Agreement seeks to significantly reduce these emissions aligned with limiting global temperature increase below 1.5°C (Republic of South Africa, 2021). Noting the heavy reliance and entrenched path dependence on coal, complying with the agreement will result in a 50% reduction in electricity derived from coal (Oyekale & Molelekoa, 2023) and a subsequent increased uptake in renewable-based energy generation. "According to the 2018 IPCC Report, coal-fired generation needs to be reduced by 78% by 2030 to keep the goal of limiting average global temperatures to within 1.5°C above pre-industrial levels within reach" (Eskom, 2022b, p.115). The International Just Transition Partnership launched at COP 26 sought to support SA's decarbonation efforts with a 8.5 billion USD deal.

Moreover, the energy generation process is extremely water-intensive; water is supplied from several freshwater systems located within proximity of the power stations, the most notable of which is the Vaal River Eastern Sub-System (VRESS) which supplies water to eleven power stations in the region (Eskom, 2018). Eskom has a license to withdraw 360 300 Ml from the VRESS per annum but has used 320 000 Ml on average across all power stations (Eskom, 2018). Much of this water will be released for other uses as coal-fired power stations are decommissioned over the next two decades. This could contribute significantly to counter-acting the negative impact of climate on water resources, in particular in the North East of the country where there is considerable agricultural potential.

State of Food in SA – overview

In addition to the semi-arid classification, South Africa is also constrained in terms of productive land - 11% is arable and heavily reliant on rainfall, 3% is considered as fertile and only 1% has suitable climate and soil combinations (GreenCape, 2022b). Moreover, agriculture is deemed central to the economy forming the basis of food provision (GreenCape, 2022b), thus a robust agricultural sector supports food security. Even so, the sector produces enough food to meet the nutritional needs of the 60 million inhabitants. This production is supported by advanced food, nutrition and agricultural programs, yet practically, these benefits do not reach many as the effects of nutrition issues (over and under nutrition), destructive agricultural practices and stark territorial asymmetries are extremely prevalent (FAO et al., 2022).

South Africa's high inequality is also reflected across the food system as food security is still strongly segregated along racial boundaries (FAO et al., 2022). A recent report from the Integrated Food Security Phase Classification (IPC), mapped the food insecurity across the country and categorised the various phases. It found that 16% of the population faced high levels of food insecurity which demanded urgent attention as these food gaps severely impacted livelihoods (Integrated Food Security Phase Classification, 2021). The report further highlighted four factors that serve as key drivers for national food insecurity, they are:

- COVID-19 – purchasing power of households was negatively affected by job losses experienced during the national lockdown.
- Economic performance and employment – the national economy is in a period of stagnation (StatsSA, 2023), resulting in job losses and reduced income, impact the ability to purchase food. Figure 3.7 shows that the population has grown faster than the economy.
- Cost of food – food price inflation has exceeded general inflation since 2015 – Figure 3.8 - which compromises the ability of people to afford food.
- Weather – as agriculture is rain-dependant, the recent drought has impacted production and reducing supply, and thereby increasing prices.

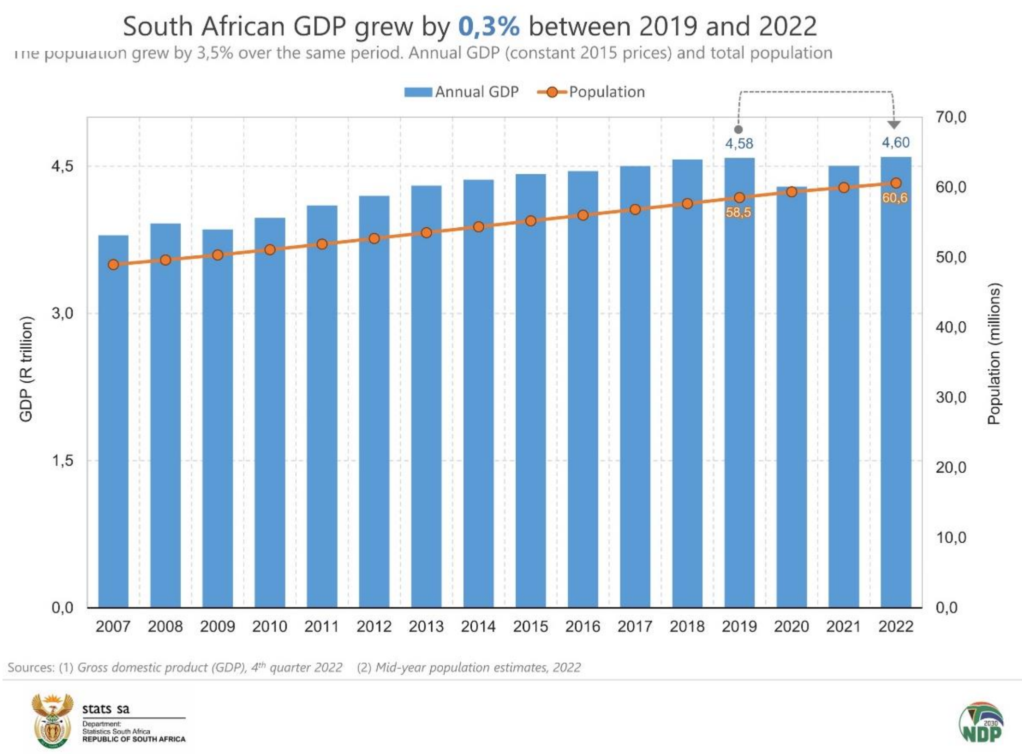

Figure 3.7: South Africa GDP vs population growth 2019-2022

(Source: StatsSA, 2023)

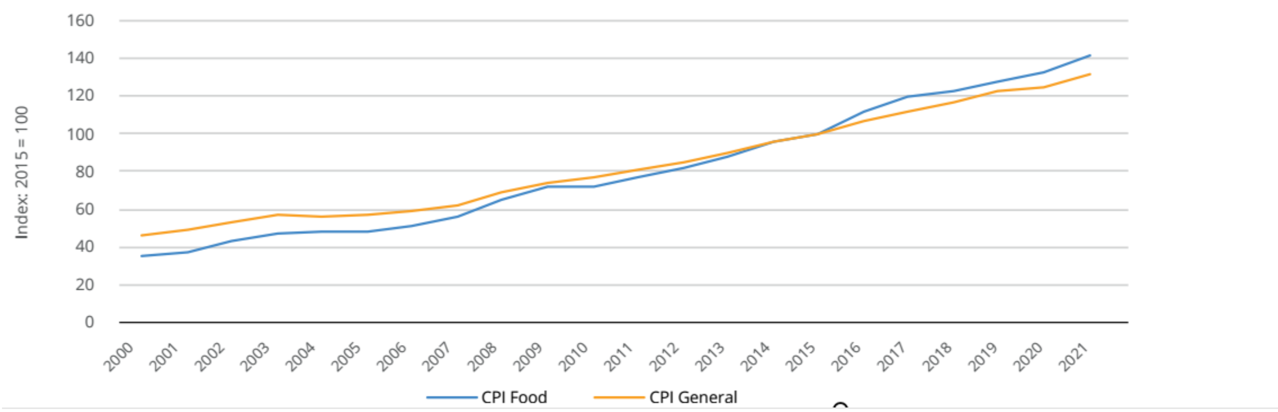

Figure 3.8: General CPI vs food CPI

(Source: FAO et al., 2022)

Agriculture was the sole sector that experienced positive growth during the height of the Covid-19 pandemic (StatsSA, 2023) which was crucial in offsetting the general economic decline and consequent job losses (GreenCape, 2022b). The sector's income rose by 46% from R107.7 billion to R157.4 billion from the 2019/2020 season to the 2020/2021 season (Directorate: Statistics and Economic Analysis, 2021). Despite having the capacity to meet national demands, the sector is highly climate sensitive. Periods of irregular climate have increased the need to import foods2, in particular, staples such as maize (FAO et al., 2022), increasing the cost of supply while compromising livelihoods and food security. The sector features as a priority in the NDC not only due to its climate vulnerability, but also due to the knock-on impacts in job-creation, economic development and its role in attracting foreign direct investment (Republic of South Africa, 2021).

The food sector is subject to market forces although the Department of Agriculture, Land Reform and Rural Development (DALLRD) and the Department of Forestry, Fisheries and Environment (DFFE) are ultimately responsible for supporting the agricultural sector. Both entities have mandates pursuant of sustainable agriculture that seeks to resolve historical inequalities, primarily through policy implementation, land reform and skills development programmes. While they are responsible for policy and land allocation, they have no direct influence on the production of food or on the supply chain within which it operates. The food system includes input component suppliers, agricultural production, livestock and fish but also processing, transportation, and all modes of retail (IFPRI, 2020).

WEF Nexus research in SA - Research limitations, gaps and opportunities

A detailed literature analysis (still in review) commissioned by the Water Research Council, undertakes a global perspective of WEF Nexus research, with its relevance to Africa. As described in the section *A call for cooperation across scales* (Botai et al., 2023), the review confirms the increase in related research post-2011, but it is worth noting that more than 90% of the published work is output from the Global North. A similar trend is noticed in the larger climate change and sustainability sciences – the lion's share of outputs is from the Global North, thus their perspective generally drives the discourse (Collyer, 2016). This presents a significant issue: the WEF nexus discourse is largely driven from a perspective and context significantly different to that of the Global South. It is widely noted that research and operationalization must be context-sensitive to avoid maladaptation and unintended consequences (Mpandeli et al., 2018; Mabhaudhi, Mpandeli & Nhamo, 2020). As climate change impacts are experienced more acutely in the South where resource insecurity and vulnerability are more common (DARA, 2012; Anguelovski, Chu & Carmin, 2014; Islam & Winkel, 2017; Eckstein, Kunzel & Schafer, 2021) it is even more important that research and operationalization efforts account for local contexts.

A recent dissertation produced in SA has taken a more local perspective on the WEF nexus while situated within the global narrative (Simpson, 2020). The author further supports that a 'one-size-fits-all' approach cannot be undertaken to address WEF Nexus issues or implementation as context,

[2] Drought events in particular, the 2015 occurrence detailed in the 'State of Water' provides such an example of import requirements.

functional elements and varying scales cannot be accounted for (Namany, Al-Ansari & Govindan, 2019; Serrano-Tovar et al., 2019).

From the perspective that the nexus discourse remains largely conceptual, Simpson (2020) undertook an extensive analysis of global metrics in order to develop a *WEF Nexus Index*. This was informed by preliminary studies, the first of which evaluated the WEF Nexus as a vehicle to achieve resource security. While the author argues that this is realistic, the growth in research and practical interest is driven in part by the resource and subsequent financial constraints experienced by private institutions. What is omitted is that these institutions must be prudent – as seen in the case of the V&A Waterfront and GCX DASH – to remain viable and can avoid the bureaucracy and institutional constraints generally prevalent in public spheres (Wichelns, 2017). Furthermore, it is becoming clear that economic growth and human development will be stymied by WEF constraints, further prompting the emergent interest (Salam et al., 2017). Later in developing the *WEF Nexus Index,* a strong correlation between data points is evident, when compared to the human development index (HDI) – see Figure 3.9. This access and consideration of development is central to securing basic humans rights but are also at the core of sustainability challenges (Mabhaudhi et al., 2019; Nhamo et al., 2020).

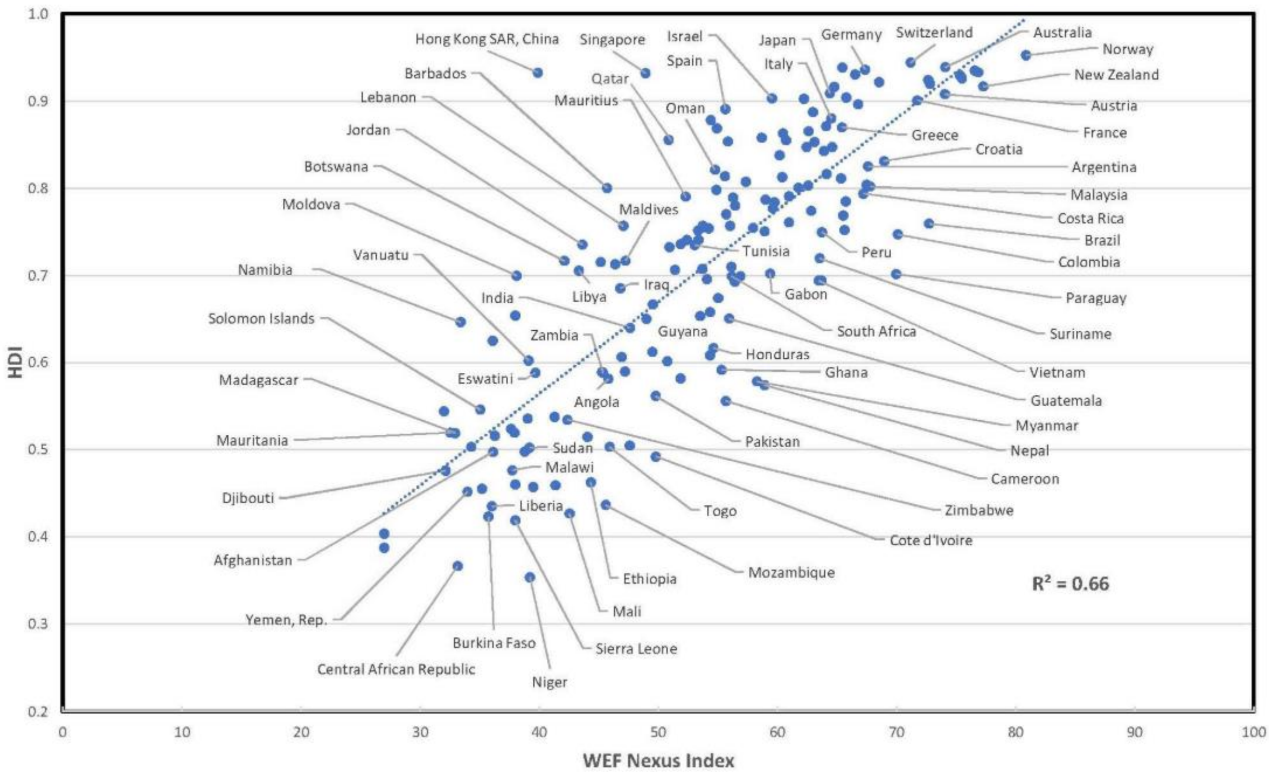

Figure 3.9: Plot of the HDI vs WEF Nexus Index (Simpson, 2020)

Despite this finding, the central critique of the WEF nexus – the lack of implementation methods – remains. Simpson (2020) investigates this in the second part of the study, seeking to move the discourse from *nexus thinking* to *nexus action*. The rationale is firstly premised on global concerns around resource security, compounded by the visible effects of climate change. Secondly, competing interests and trade-offs of competing sectors in the nexus need to be holistically (and optimally) managed while finally, understanding the WEF nexus is a vehicle by which the SDGs can be realized (Simpson, 2020). The author also highlights that governance considerations are largely absent in discourse and analysis, supported by Stirling (2015) who argues that the relationships between actors and their networks across multiple domains, coupled with governance arrangements needs to be understood and accounted for, which is the third and final aspect. But this must be prefaced by contextual understanding of the interactions between WEF which is glaringly absent (Albrecht, Crootof & Scott, 2018) and could be greatly supported by the availability of more robust resource data, also largely missing.

Thereafter, the research provided a local case-study of the WEF nexus in Mpumalanga. The case details a practical example of the intersection of water, energy and food in the province, where the impacts of competing decisions and interests become evident. The region experiences an ongoing friction between agriculture and coal mining (Simpson, 2020). Of the high potential arable land detailed in the section *State of Food,* 46% of the national land is located in the province, which is also where power stations have been located in proximity to abundant coal reserves (see section *State of Energy).* A quarter of this coal is exported, and another sizable portion is used for coal-fired power generation which supports the local economy, but agriculture in the region supports national food security and both have different yet competing water demands and environmental footprints (Simpson, 2020). "Current and future mining activities will have a significant negative impact on agricultural production, as well as long-term implications for food prices and food security" (ibid, p.36). Balancing these competing requirements is key to development and security but requires coordination and integration between numerous stakeholders, coupled with a reduced reliance on coal-based energy. The study is concluded with the following: WEF nexus analysis, supported by robust data, is required to influence integrated public policy and support decision-making to promote the sustainability of the region (Simpson, 2020)

Overall, the study resulted in several significant findings – primary of which was the novel establishment of a country-level composite indicator, comprised of several variables from publicly available data. In essence, it provided a quantitative means to describe the access, availability and consumption of water, energy and food – indicating current progress. Nhamo et al. (2020) also produced an analytical tool, using similar inputs to visually depict national WEF access, availability and productivity to develop a set of WEF nexus indicators – see Figure 3.10. Ideally, the graph should be maximized and balanced, which would indicate that 'resources are being developed and utilized holistically to achieve sustainability' (Nhamo et al., 2020, p.20). Any deformation in the shape would indicate an issue, onset by a maladaptation from a sectoral approach, indicating where intervention would be required.

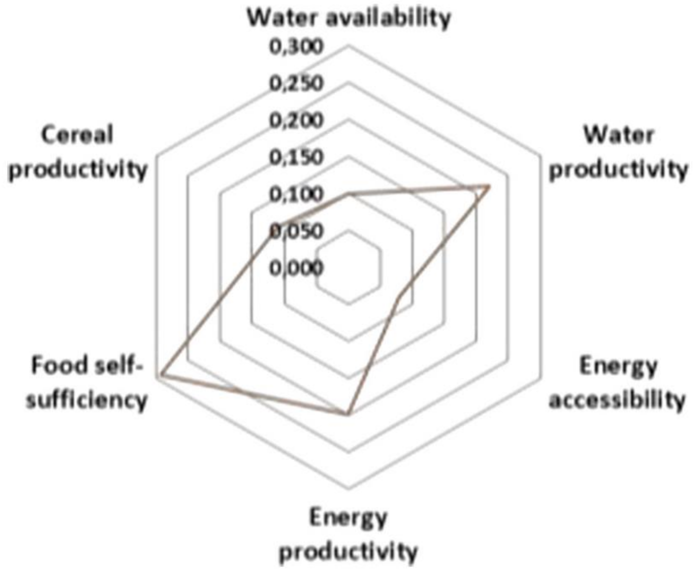

Figure 3.10: Performance of WEF Nexus indicators for South Africa in 2018 (Nhamo et al., 2020)

As useful as these outputs are, practical guidance towards operationalization remains sparse. Despite the wide-ranging critique and potential of implementation, global and local scholars agree that the availability, reliability and access to robust data across scales to develop tools and conduct analyses strongly constrains research (Lawford et al., 2013; Biggs et al., 2015; Kaddoura & Khatib, 2017; Laspidou et al., 2020; Nhamo et al., 2020; Opejin et al., 2020; Simpson, 2020). In contributing a theory of change framed towards implementation, Naidoo et al. (2021) centralizes the role of governance and institutions. For these scholars, success would require transformations that would align policies with nexus strategies and overcome the inherent limitations of sector-based planning. Outputs from analytical tools are useful in identifying where interventions are required, as evidenced in Nhamo et al.(2020) and Simpson (2020).

Having developed this theory of change, the mechanism by which to operationalize the WEF nexus remains unanswered (Naidoo et al., 2021). However, Naidoo et al provide a conceptual foundation for moving from 'WEF nexus thinking to WEF nexus action'. Six 'levers' are established in the framework, each leveraging the outputs of the predecessor. It describes the following:

1) Establishing effective nexus outputs through evidence using tools, experiments and innovations contributing to an increasing capability base.
2) Accounts for the additional capacity required in different contexts to deploy said evidence.
3) Combines and mobilizes the capability with the capacity to manage the governance and operationalization in generating a supportive policy framework.
4) Management of the effects of change within and across research, governance and policy agencies but also resource sectors.
5) Packages the nexus system for deployment at other scales for polycentric and transformative change. Cascading environmental effects (external) and new WEF nexus capabilities (internal) are sought and continuously developed.
6) Capacities and capabilities are renewed and reconfigured to account for changes, but also to incorporate innovations, alliances and updated policy

(Naidoo et al., 2021)

Understanding the WEF nexus operationalization is context specific, and still in its infancy in South Africa. It is now clear that it is a framing that is helpful for addressing regional challenges that include:

- Challenges onset by climate change. It has been said to connect water, energy, food and climate to the economy (Naidoo et al., 2021)
- Land degradation (Naidoo et al., 2021) and national land-use considerations and trade-offs (Simpson, 2020)
- Reducing and limiting fuel-based emissions associated with energy generation. This is currently hampered by numerous factors, one of which is investment (Mpandeli et al., 2018)
- Achieving water security increase constraints, pressures and demand (Lawford et al., 2013; Ding, Gilligan & Hornberger, 2019; World Economic Forum, 2021)
- Increased population growth coupled with urbanization (Naidoo et al., 2021), coupled with the effect on land use and food demands
- Critically, the lack of economic modelling scenarios that account for climate change impacts on the WEF for the Global South context.

In setting the research agenda, this workstream aims to investigate these aspects from the perspective of the WEF nexus and climate change, and in particular the investment and capacity requirements in response to these aspects. This also illuminates the time, expertise but primarily the finance required for operationalization, for which current research does not provide means or surety (Zhang et al., 2020).

Setting the research agenda

In light of the above literature review and given the obvious empirical resource challenges facing South Africa, the following research agenda is proposed. Led by the National Treasury's SA-TIED initiative (SA-TIED, n.d.), this research agenda is a collaborative effort by several public institutions and South African Universities. The public institutions working with National Treasury include the National Planning Commission, the Presidential Climate Commission and the Development Bank of Southern Africa. The South African Universities include University of Cape Town, University of Stellenbosch, University of the Witwatersrand and University of Pretoria. Not only will this be the first comprehensive analysis of these three sectors and their intersectional dynamics, it also will be the first time this cluster of public institutions and universities have collaborated in this unique manner with respect to the WEF nexus challenges, supported as they are by such large, publicly funded research budgets (mainly provided by the DBSA and the SA-TIED project).

The research programme is coordinated by the Water, Energy and Food in the context of Climate Change Workstream (WEF CC Workstream) of SA-TIED Phase 2. This workstream is led by Georgina Ryan from the National Treasury as the policy lead, and Professor Mark Swilling, Co-Director of the Centre for Sustainability Transitions in Stellenbosch University as the academic lead. The WEF CC workstream is one out of the six workstreams that make up Phase 2 of the SA-TIED Programme (SA-TIED, n.d.).

Extensive research work by specialists in each of these sectors exists, and the NRF is funding two large integrated projects on the Water-Energy-Food Nexus[3] that involve SA and international partners. The overriding research question that the WEF CC Workstream will address is as follows: what system changes (policy, regulatory, institutional, financial) are required to ensure that South Africa has long-term sustainable supplies of energy, water and food? What, in particular, are the related investments required to achieve this? What are the long-term economic consequences of sustainable supplies of energy, water and food relative to a business-as-usual scenario?

While conventional policy analysis tools will be used to address question one, considerable emphasis will be given to the financial analysis of the investment requirements for achieving energy security/Net Zero, water security and sustainable and affordable food supplies. The WEF CC Workstream will use an adapted version of the World Bank's Beyond the Gap analytical framework for this purpose, that is structured according to the following analytical logic (Rozenberg & Fay, 2019):

Figure 4.1: Analytical diagram of the World Banks's Beyond the Gap framework

(Source: Rozenberg & Fay, 2019)

Modelling tools will be used that will build on the SATIM-GE model developed by UCT during Phase 1 of SA-TIED (Merven et al., 2018). By leveraging the research and modelling expertise of the teams and progress made during Phase 1, this research aims to make a contribution to a deeper understanding of the conditions that could result in a just transition in South Africa if the appropriate policy and financial decisions were made.

Investment requirements to achieve energy security and net-zero by 2050

Context

South Africa's energy challenges are well-known: 85% of South Africa's energy is generated by coal-fired power stations, compared to a global average of 34%. The CO2 content of South Africa's economic output is the highest in the world. As the world transitions to low carbon energy sources (with total investments now over $500 billion pa, which is double total investments in fossil fuels and nuclear combined), South Africa faces carbon border taxes on its exports, in particular to Europe but soon to other countries. In addition to having some of the best solar and wind resources in the world, this global transition comes at a time when South Africa's fleet of coal-fired power stations is ageing and needs to be decommissioned.

The Integrated Resource Plan stipulates that 11 000 MW of coal-fired power must be decommissioned by 2030, and 26 000 MW of renewables must be constructed. With 7 years to go, these targets are

[3] https://www.nrf.ac.za/call-for-pre-proposals-dutch-research-council-nwo-and-national-research-foundation-nrf/

unlikely to be achieved if nothing changes. The National Planning Commission has called for an 'energy emergency' and an accelerated rollout of renewables to end loadshedding in two years. All the research teams analysing investment requirements through to 2050 to achieve Net Zero by then agree that the cost is between $250 and $950 billion (see Table 2). The bulk of this investment will be from private sector investors, both local and international. At this stage, there is no evidence that additional coal-fired power stations will be fundable from public or private sources, whether local or international. However, a gas-fired backup and storage system will be required to support variable solar and wind generators, but this could be green hydrogen when the cost of hydrogen drops from $5/kg to around $1/kg. Nuclear energy remains far too expensive, although in a decade or so small modular reactors might become an option.

For decades, governments across the globe have collectively committed to multi-national agreements, promulgated laws, and developed national strategies aimed at reducing greenhouse gas emissions (UNFCCC, 2016, 2021). South Africa, along with many other countries, is a signatory of the Paris accord of 2015 (UNFCCC, 2020). Within a domestic context, South Africa's constitution recognises the need to prevent air pollution and ecological degradation as a basic human right (South Africa Government, 2012). This results in a collection of national strategies on how air pollution could be reduced to prevent further climate change (DoE, 2019; DEFF, 2020; NPC, 2012). These commitments and strategies are contradicted by South Africa's ever-rising carbon emissions, thus, disregarding its own climate pledges.

South Africa's particular challenge, however, is not about adhering to global climate commitments for the sake of protecting the environment. This is important, but it is secondary to the challenge of energy security. Significantly, achieving energy security in the fastest and cheapest way also results in the decarbonisation of the economy. The reason for this is that renewables plus battery and gas backup are now a cheaper way to ensure energy security than depending on coal-fired power. It is clear that public and more especially private finance is essential to achieve the net-zero goal. So, the question then becomes, what are the investment requirements to achieve net by 2050?

Table 2: Estimates of investment required to achieve net zero from various sources

Source	Budget Timeline		Sector
	2030	2050	
JET-IP*	$98bln (2027)	-	Economy-wide
BFT & CST	-	$250bln	Energy
UCT*	$180bln	$933bln	Economy-wide
NBI*	$66bln	$393bln	Economy-wide
World Bank	$86bln	$953bln	Economy-wide
ESKOM	$80bln	-	Energy

(Source: Nicholls (2022); World Bank (2022); NBI (2022); PCC (2022); Macmillan-Scott, et al (2022); The Presidency (2022). Authors conversion rate = 15:1).

The table above shows that several institutions have modelled transition pathways along with investment requirements. These models assessed decarbonisation pathways with respect to the energy sector or on an economy-wide basis. The report by the Blended Finance Taskforce (BFT) & Centre of Sustainability Transitions (CST) reveals that the journey towards a full energy transition will require capital investments of between 2 – 2,3% of South Africa's GDP per year. The total investment requirement for the energy sector alone through to 2050 would be $250 billion. The Just Energy Transition – Investment Plan (JET-IP) released by the South African Government at COP 27 in 2023, the National Business Initiative (NBI), the University of Cape Town (UCT) and the World Bank have used an economy-wide lens to generate their estimates. Their estimates range from 3.3% to 8% of GDP per year (Macmillan-Scott et al., 2022; NBI, 2022; Nicholls, 2022; The Presidency, 2022; World Bank, 2022). The BFT & CST report estimated that just over $176 bn of the $250bn would come from private sector sources and the remainder would be covered by public finance (development finance, government, philanthropic initiatives) (Macmillan-Scott et al., 2022). Based on the NBI, BFT & CST, and UCT estimates, the investments will be required in six main areas: (i) renewable energy generation infrastructure; (ii) storage (battery and pumped hydro); (iii) gas backup; (iv) transmission and distribution; (v) early retirement of coal power stations; and Justice for workers and communities.

Primary Research Question

Taking into account the future impacts of climate change and the global dynamics of the energy transition that is underway, what investments are required between now and 2030 that will ensure that it will be possible to achieve the energy and carbon targets as specified in the National Development Plan (NDP), the PCC's Just Energy Transition Framework, the Just Energy Transition Investment Plan, the South African NDC and the National Infrastructure Plan 2050?

Supplementary Research Questions

To answer the primary research question, the following supplementary questions will need to be addressed:

- What is the funding gap between current levels of investment in energy infrastructures and what will be required to achieve the relevant energy and carbon SDGs and NDP goals, covering capital, operations and maintenance spending?
- What policy and regulatory frameworks are in place that govern the flow of public and private investments in energy infrastructure and service delivery with respect in particular to technologies, service levels and resilience in the face of climate change?
- Given the probable impacts of climate change on the global commitment to decarbonization over the coming decades, what should the financing targets be for optimizing achievement of the energy and carbon SDGs and NDP goals by 2030?
- What policy and institutional changes will be required to enable this increased level of investment in climate resilient energy infrastructure and services to achieve the NDP and SDG targets?

Research Strategy

The PCC, NPC and DBSA have agreed to cooperate with SA-TIED with respect to an analysis of the energy sector within the wider policy framework set by the Cabinet approved National Infrastructure Plan 2050 (DPWI, 2022). A Steering Committee chaired by Professor Sampson Mamphweli from SANEDI will comprise representatives from NT, NPC, PCC and DBSA. The DBSA and PCC will provide the funding for the research and procure the professional team. The professional team will report to the Steering Committee which will, in turn, meet regularly to provide the professional team with strategic direction. The research work will build on South Africa's well-developed energy modelling capabilities, with three major centres of excellence (Eskom, CSIR and UCT) providing useful information.

The overall objective of this study is to assess energy infrastructure investments required between now and 2030 (extending to 2040 and 2050), to achieve the energy and carbon targets of South Africa as well as the associated economic and socio-economic impacts of implementing climate mitigation policies. The specific objectives of the study are to:

- Quantify climate pathway scenarios and energy infrastructure investments required to meet energy and carbon targets as specified in the NDP, the South African NDCs, and the SDGs;
- Quantify pathway scenarios and energy infrastructure investments required to meet South Africa's Just Energy Transition Framework taking into account the potential impact of current energy and climate policies, plans and regulations;
- Conduct high-level economic and socio-economic impact assessments for shortlisted climate, infrastructure investments and JET pathways scenarios (maximum of 3 scenarios to be selected);
- Where the developed pathway scenarios suggest a rapid roll-out of renewable energy projects outside the current policy environment, quantify these investment needs and highlight policy gaps. Also indicate what is possible for the private sector to invest, and what risk mitigation is still required for these projects;
- Develop a methodology to assess other analyses and outputs within a "comparable common frame," allowing the Parties to corroborate as well as critically evaluate each of these prior to developing their own perspective against the NDC range that is most feasible for the JET;
- Identify and adapt the most appropriate methodological and modelling approach/es for mitigation costing analysis and economic impact assessment for RSA. This will include an analysis of the methodologies and assumptions underlying studies that have already been conducted, and compare or critique these, including carbon budget assumptions as described in the NDC;
- Develop estimates of the marginal cost of carbon abatement in RSA using various technologies, acknowledging that policy uncertainty remains regarding the selection of mitigation pathways, considering the cost of transition and other barriers;
- Assess the anticipated sectoral and industrial shifts, investment requirements, and socio-economic implications of climate mitigation action across the RSA economy until 2050, with reference to the range of carbon abatement parameters contained in the NDC.
- Set out key uncertainties and strategic policy options required to achieve SDG 7, NIP2050 and NDP goals, as well as long-term climate mitigation economic planning along with recommendations, taking into account the various costs/funding, climate, economic and social impacts of critical policy choices;
- Identify investment barriers and financing gaps and highlight infrastructure cost drivers and the implications of different policy choices;
- Engage policy makers and implementation agencies, to the extent possible, to work through the implications of policy choices and their trade-offs, in terms of costs and service levels.

Financial analysis of the investment requirements to achieve water security by 2050

Context

Historically, increases in water use have tracked economic growth rates. However, there is a physical limit to the availability of water. The result is that many policy frameworks since 1994 have emphasized the need for greater water efficiency in order to decouple economic growth rates from rates of water use over time. This is also a global challenge, although in a number of jurisdiction water consumption rates have decoupled from economic growth rates (UNEP, 2015). However, as the impacts of climate change become more pronounced and severe, the need for this kind of decoupling has become more urgent (UNEP, 2015; IRP, 2019). The Day Zero event in Cape Town in 2018 brought this challenge clearly into focus (Simpson, 2020; Ding et al., 2019).

The preliminary results as of April 2023 of the first phase of research by the team appointed to do the water research reveals that there is a huge gap between current levels of investment in water and sanitation services and what would be required to achieve "universal access to individual services on the property", which is a standard consistent with SDGs 6.1 and 6.2, and the NDP goals. Current levels of investment are between R34 and R38 billion per annum, which is roughly a quarter of the required levels of investment. To achieve universal access, annual investment levels in water and sanitation services would need to be between 2.3% and 2.7% of GDP, which is the equivalent of between R121 billion to R131 billion per annum. The preliminary research suggests that the large gap between current levels of investment and what is required has much to do with declining quality of existing infrastructure due primarily to management deficiencies and the weakening of local government capacity to manage networked infrastructures. No matter the combination of public and private sector investments that arise, ultimately the revenues to ensure financial viability and sustainability will have to come from either increased tariffs or increased allocations from the fiscus, or both. How different financial flows are blended will affect risk, cost of capital and time frames. Reducing the cost of non-revenue water from the current 41% to 20% and counteracting invasive alien plant infestation can offset the rising costs of water security.

Primary Research Question

Taking into account the future impacts of climate change on South Africa's water resources, what investments are required between now and 2030 that will ensure that it will be possible to achieve the water targets as specified in the National Development Plan (NDP) and the Sustainable Development Goals (SDGs)?

Supplementary Research Questions

To answer the primary research question, the following supplementary questions will need to be addressed:

- What is the funding gap between current levels of investment in water infrastructure (from bulk through to service delivery) and what will be required to achieve the relevant water and sanitation SDGs and NDP goals, covering capital, operations and maintenance spending?
- What policy and regulatory frameworks are in place that govern the flow of public and private investments in water resources and service delivery with respect in particular to technologies, service levels and resilience in the face of climate change?
- Given the probable impacts of climate change on water resources, what should the financing targets be for optimizing achievement of the water and sanitation services SDGs and NDP goals by 2030?
- What policy and institutional changes will be required to enable this increased level of investment in climate resilient water resources and services to achieve the NDP and SDG targets?

Research Strategy

The PCC, NPC and DBSA have agreed to cooperate with SA-TIED with respect to an analysis of the water sector (including both bulk water resources and water services) within the wider policy framework set by the Cabinet approved National Infrastructure Plan 2050 and the SDGs. As of the time of writing (April 2023), the DBSA has tendered and procured the services of a professional team. A Steering Committee has been established to guide the research, chaired by Amanda Gcanga from the World Resources Institute The Steering Committee comprises representatives from the four partner institutions.

The Western Cape Economic Development Partnership (which is funded by the government) has agreed to make available their extensive analysis of the long-term water strategy challenges facing the Western Cape in the face of climate change. This will serve as a case study that will highlight the practical implications of climate change on water resources of a region, and the related investment challenges facing the City of Cape Town.

The focus of this phase of work is on improving the modelling of water resources and so no additional water services scenarios will be run. The water services scenarios will therefore include two scenarios related to service level goals and four related to technology options.

The two scenarios related to service level goals are:

- Universal basic servicing.
- Achievement of SDG6.1 and SDG6.2.

'Universal basic servicing' allows for water and sanitation services to be shared between up to five households in urban informal and rural traditional areas, corresponding to the United Nations' Joint Monitoring Programme (JMP) definition of 'basic' and 'limited' services for water and sanitation respectively. This is consistent with current South African water sector policy on basic service access, and it is also consistent with the global Beyond the Gap methodology.

The achievement of SDG 6.1 and 6.2 uses the strict definition of safely managed services as a target, which includes universal access to individual services on the property. This is included largely for comparative purposes and to highlight some of the technical, financial and political trade-offs relevant to the debate on closing water and sanitation service gaps.

The four technology options are specified as follows:

- A full conventional option provides services using the current technology mix (status quo).
- A low-cost option prioritises the lowest cost technologies, and shared services wherever possible (given the applicable goal).
- An alternative technologies option attempts to minimise water use and energy use in the collection, storage, transport and treatment of water and wastewater.
- A Water Conservation and Demand Management (WCDM) option is specified with the same technology mix as the alternative technology scenario but pushes demand reduction measures to what can be considered the maximum feasible level. All other scenarios contain a target to reduce losses to 26% (i.e., a 15% reduction from 41%) and demand management to limit excessive consumption. The WCDM scenario reduces the technical losses further, down to 20% by 2030, and remaining at this level thereafter.

Land-use implications of future food needs in the face of urbanisation and population growth

Context

The NDC (Republic of South Africa, 2021) and Low Emissions Development Strategy (DFFE, 2020) sets the framework for analysing the future of food resources from a climate adaptation and resilience perspective (see Figure 4.2 below). Following the South Africa report to the FABLE Consortium compiled by Dr. Odi Simelane and colleagues (Selomane & Reyers, 2020), if current trends continue, South Africa can expect low population growth (from 58 million in 2020 to 67 million in 2050), no agricultural expansion, no afforestation target, low productivity increases in the agricultural sector, an evolution towards a high-sugar-content and processed-food diet (including meats and fat), and no change in postharvest losses. This corresponds to a future based on current policy, risks, and historical trends that would also see considerable advances in biodiversity loss, soil degradation and loss of agricultural land because of urbanization. This projection is premised on the assumption that the global GHG concentration trajectory would lead to a radiative forcing level of 6 W/m2 (RCP 6.0), or a global mean warming increase likely between 2°C and 3°C above pre-industrial temperatures, by 2100. The corresponding climate change impacts on crop yields by 2050 for corn, rice, soyabean, and wheat have been calculated by researchers and the results are alarming, to say the least. The alternative lies in adopting sustainable policies and practices that could reduce food losses, promote healthier diets, restore soils and catalyse sustainable land-use practices.

Table 1 | Summary of the mitigation target, sectoral coverage, and references to biodiversity and spatially-explicit planning in current NDC

	Total GHG Mitigation					Mitigation Measures Related to AFOLU (Y/N)	Mention of Biodiversity (Y/N)	Inclusion of Actionable Maps for Land-Use Planning[1] (Y/N)	Links to Other FABLE Targets
	Baseline		Mitigation target		Sectors included				
	Year	GHG emissions (Mt CO_2e/yr)	Year	Target					
NDC (2015)	N/A	N/A	2025-2030	398-614 Mt CO_2e	Energy, industrial processes & product use, forestry, agriculture, and other land use	N	Y	N	Food security, water, afforestation
LT-LEDS (2020)	N/A	N/A	2025-2030 (398-614 Mt CO_2e)	2050 (212 - 428 Mt CO_2e)	Forestry, agriculture	Y	Y	N	

Note. "Total GHG Mitigation" and "Mitigation Measures Related to AFOLU" columns are adapted from IGES NDC Database (Hattori, 2019)
Source. South Africa's Department of Environmental Affairs (2015b, 2020)

Figure 4.2: Table showing mitigation target and sectoral scope to NDC.

(Source: Selomane & Reyers, 2020)

Primary Research Question

Taking into account the future impacts of climate change on South Africa's food resources, what investments are required between now and 2030 that will ensure that it will be possible to sustainably produce sufficient nutritious food as specified in the National Development Plan (NDP) and the Sustainable Development Goals (SDGs)?

Supplementary Research Questions

To answer the primary research question, the following supplementary questions will need to be addressed:

- What is the funding gap between current levels of investment in sustainable land-use and biodiversity management to ensure long-term sustainable supply of food and what will be required to achieve the relevant food-related SDGs and NDP goals?
- What policy and regulatory frameworks are in place that govern the flow of public and private investments into sustainable food production with respect in particular to technologies, natural resource management and resilience in the face of climate change?
- Given the probable impacts of climate change on food resources, what should the financing targets be for optimizing achievement of sustainable food production and consumption as per the SDGs and NDP goals by 2030?
- What policy and institutional changes will be required to enable this increased level of investment in climate resilient food production and consumption to achieve the NDP and SDG targets?

Research Strategy

Given that the Terms of Reference for the Workstream emphasizes dealing with food in the context of climate change and in relation to energy and water, it is necessary to contextualise the food challenge within the wider challenge of climate change adaptation. The PCC has strongly recommended this orientation. At the same time, it needs to be recognized that unlike energy and water, there is no central state apparatus responsible for the regulation and delivery of food. It is a sector that is driven by a vast multiplicity of market players. Nevertheless, an adaptation focus helps to emphasize the underlying resilience dynamics such as land-use and biodiversity loss.

Dr. Odi Selomane (former International Director of the Programme for Ecosystem Change and Society (PECS)) and now based at University of Pretoria will lead this research project. Ideally, this study should also be conducted using an adapted version of the Beyond the Gap methodology. But this may not be possible given that the food system, unlike the water and energy system, is not directly controlled by state agencies.

Dr. Selomane's research will build on the work he and his colleagues did for the 2020 FABLE Report in Pathways to Sustainable Land-Use and Food Systems produced by the International Institute for Applied Systems Analysis, Sustainable Development Solutions Network and The Food and Land Use Coalition (Selomane & Reyers, 2020). Using a 'pathways' perspective (Swilling et al., 2022), the research strategy is premised on a distinction between a Current Trends Pathway and Sustainable Pathway. The Current Trends Pathway assumes a global GHG concentration trajectory that would result in a radiative forcing level of 6 W/m2 (RCP 6.0), which would mean a likely 2 to 3 degrees warming by 2100 over pre-industrial levels. The Sustainable Pathway assumes a GHG concentration trajectory resulting in a lower radiative forcing level of 2.6 W/m2 by 2100, which is consistent with limiting warming by a maximum of 2 degrees. While the Current Trends Pathway would have devastating impacts on South Africa's food supplies, the Sustainable Pathway could have more beneficial outcomes. Building on this research, more specific policy interventions and related investment requirements will be worked out.

Climate modelling for future climate change impacts on food, energy and water systems

Context

South Africa has a well-developed and well-funded climate science community with many scientists playing important roles at international levels. There is a sufficient scientific consensus that South

Africa faces numerous climate change impacts. A vast literature now exists about these impacts (Mbokodo et al., 2020; Waggoner, 1983; Vandentorren et al., 2006). Consistent with global trends (IPCC, 2021; Kruger & Sekele, 2013), recent research shows that daily minimum and maximum temperatures across South Africa are rising (Kruger & Shongwe, 2004; Kruger & Sekele, 2013; MacKellar, New & Jack, 2014). Indeed, mean temperatures may well be rising at double the global rate in tropical and sub-tropical zones across central and southern Africa (Engelbrecht et al., 2015). In South Africa, more heavy rainfalls have been observed as well as an increase in intensity of these events, leading to flooding (Burls et al., 2019). Colder temperatures are decreasing, and warmer temperatures are rising (Kruger & Nxumalo, 2017). However, it is heatwaves (HW) that could have the most devastating impacts on health, food, energy consumption and water supplies. There is clear evidence that there is a substantial increase in the annual number of HW days in South Africa (Mbokodo et al., 2020).

Primary Research Question

What are the primary climate change impacts on South Africa's water, energy and food resources over the short-, medium- and long-term?

Secondary questions:

- What is the state of knowledge about global climate change impacts on the Southern African and South Africa regional social-ecological systems?
- What are the specific impacts of climate change on the water, energy and food sectors without and with adaptation measures?
- What adaptation measures would be most appropriate to limit the most negative impacts?

Research Strategy

Professor Francois Engelbrecht from the Wits Institute for Global Change will lead this research project. Building on previous work (Mbokodo et al., 2020; Engelbrecht et al., 2015), he will deploy the Conformal Cubic Atmospheric Model (CCAM) developed by the Commonwealth Scientific and Industrial Research Organization (CSIRO) in Australia, coupled with the CSIRO Atmosphere-Biosphere Land Exchange Model (CABLE), and in combination with six different Global Climate Models (GCMs). CCAM is a global model, but it can be used to develop regional climate models (RCMs) if sufficient data and capacity exists to parametrize the model using a stretched-grid variable-resolution mode (Mbokodo et al., 2020). Working with South Africa Weather Service data, it was possible to develop analyses of the changing frequency, duration and intensity of HW events over different periods, namely 1983-2012, 2010-2039, 2040-2069 and 2070-2099 (Mbokodo et al., 2020). This research will provide the basis for a more in-depth analysis of the impacts of these HW events in particular, plus other climate dynamics where relevant, on the future supplies of food, energy and water within the South African context. It will be worth exploring whether HW incidents could be used as the primary 'climate damage factor' that will be required to develop a modelling tool (see next section).

Modelling Review and Assessment

Context

During the course of SA TIED Phase 1, UCT researchers led by Bruno Merven further developed their SATIM-GE model. In their SA-TIED paper *Climate Mitigation in South Africa* Merven et. al. assess the models that have been developed to analyse South Africa's existing and potential carbon trajectories

(Merven et al., 2021). Two tables from this report describe the most significant studies that have been done:

Table 1: Mitigation pathway studies for or including South Africa

Reference	Name of study
Winkler (2007)	Long-term Mitigation Scenarios (LTMS)
ERC (2011)	South African Low Emissions Pathways Project (LEPS)
DEA (2014)	South Africa's greenhouse gas mitigation potential analysis (MPA)
ERC (2015)	Quantifying uncertainty in baseline projections of CO_2 emissions for South Africa
Altieri et al. (2015)	Pathways to deep decarbonization in South Africa (DDPP)
DOE (2016)	Integrated energy plan report (IEP)
Zhang (2017)	Actions towards decarbonization – Climate policy assessment and emissions modelling with case study for South Africa.
NCI (2017)	Greenhouse gas mitigation scenarios for major emitting countries. Analysis of current climate policies and mitigation pledges: 2017 update
DEA (2018a)	Alternative greenhouse gas emission pathways for South Africa (Pathways)
DEA (2018b)	Policies and measures report (PAMS)
CAT (2018)	Scaling up climate action. Key opportunities for transitioning to a zero emissions society.
IEA (2019)	Africa energy outlook 2019. World Energy Outlook Special Report
McCall et al. (2019)	Least cost integrated resource planning and cost-optimal climate change mitigation policy - Alternatives for the South African electricity system

Table 2: Power sector studies for South Africa

Year	Name of study
IRENA (2015)	Africa power sector: Planning and prospects for renewable energy
Wright et al. (2017)	Formal comments on the Integrated Resource Plan (IRP) update assumptions, base case and observations
Chartan et. al. (2017)	Preliminary findings of the South Africa power system capacity expansion and operational model study
Wright et al. (2018)	Formal comments on the Draft Integrated Resource Plan (IRP) 2018
Merven et al. (2018)	Quantifying the macro- and socio-economic benefits of a transition to renewable energy in South Africa
Oyewo et al. (2019)	Pathway towards achieving 100% renewable electricity by 2050 for South Africa.
DOE (2019)	2019 Integrated Resource Plan report
Meridian Economics (2020)	Ambitions project

Figure 4.3: Table of mitigation pathway studies and power sector studies from SA

(Source: Merven et al., 2021)

To support the SA TIED work and other policy-relevant initiatives (e.g., the NDC), the UCT researchers developed the SATIM-GE model. It is worth quoting them in full from this report:

> "In this paper, the linked energy-economic model for South Africa, SATIMGE, is used to assess the mitigation potential of the energy sector in the country and the associated macro- and socio-economic impacts related to changes in the energy system. SATIMGE is a hard-linked coupling of the South African TIMES (SATIM) and computable general equilibrium models

> (eSAGE) (see Arndt et al. 2016 and Merven et al. 2017). SATIM is a bottom-up integrated energy systems model which captures both energy sector and process emissions. eSAGE is dynamic recursive, economy-wide of South Africa, based on the generic static and dynamic CGE models described in Lofgren et al. (2002) and Diao and Thurlow (2012). The modelling methodology, which follows that proposed by Lanz and Rausch (2011), addresses the shortcomings of single or extended models that either do not consider the energy system in appropriate detail or provide an aggregate assessment of economic indicators, whilst providing a consistent framework for assessing energy and energy mitigation policies and measures. Key developments in SATIMGE have been made since previous mitigation assessments using the same methodology. These changes are detailed in Merven et al. (2018; 2019a; 2019b; 2020a; 2020b) and Hartley et al. (2019). To assess the full emissions impact, the energy model is further dynamically linked to spreadsheet models that (separately) model waste and AFOLU." (p.9)

It goes without saying that models are necessary for making sense of possible futures in light of the past and present trends. This helps policy makers to understand the implications of the decisions they are making today. To this extent, these models are of great significance. They require a vast range of inputs. However, they also contain assumptions that need to be interrogated. For the purposes of this WEF CC Workstream, it is particularly important to assess the macro-economic implications of future investments in energy, water and food security within an overall response to climate change and sustainability in general. For this, a model (or models) will be required that includes a climate change damage function (Peng et al., 2019) and the dynamics of finance/financial flows. The South African models do not include these two dimensions which, in turn, makes it difficult to properly assess the macro-economic implications of future investments in energy, water and food security.

As the energy transition discourse intensifies in South Africa, SATIM-GE has become one of the most important and influential tools used to establish transition pathways, investment requirements and the least-cost optimal energy plan (Merven, 2020; Merven et al., 2019; Nicholls, 2022). What makes SATIM-GE unique in the South African context, is that it couples the SATIM energy model and the eSAGE model which is, in turn, based on a general equilibrium perspective (Hartley et al., 2019; Merven et al., 2019). This integration is recursive in nature. More precisely, the eSAGE model has two core GDP-related variables comprising (a) three aggregated sectors, namely agriculture, industry and services, and (b) household income which are assumed to drive up energy demand on the SATIM model (Merven, 2020; Merven et al., 2019). The eSAGE model provides the energy-related macro-economic variables, including a power sector productive function for all energy activities, electricity prices, expenditure on expansion plans, and energy consumption function of households onto the eSAGE model (Merven, 2020). After multiple iterations, the energy mix, investment requirements and emissions are generated as a result from the SATIM model, and the socio-economic outcomes such as welfare, employment and GDP are outputs of the eSAGE model (Merven, 2020). With this approach, the SATIM-GE model is able to run several scenarios and extract the trade-offs between socio-economic development and mitigation goals.

SATIM-GE is an extremely useful tool for assessing energy policy options in light of changing circumstances. However, because it does not include a climate damage function, it is not possible to quantify the economic impacts of changes in temperatures over time. The lack of a fully-fledged economic model that includes finance and the absence of a damage function constrains the ability of the SATIM-GE to provide a useful macroeconomic assessment of key risks (such as over-debtedness, deficits in the balance of payments, premature asset stranding, exchange rate tensions etc.)

associated with transitioning towards sustainable energy technologies (Giraud, 2022; Ndovela, 2023; Swilling, 2022). Although SATIM-GE may not have been designed for this, it does provide a useful foundation for achieving a more integrated economy-climate-energy model. This may mean, however, moving away from a 'general equilibrium' model, to what is increasingly being referred to as non-equilibrium hybrid models. For example, the Green Swan Report by the Bank for International Settlements recommends that Central Banks seriously consider hybrid models if they want to integrate climate change into their macro-economic assessments (Bolton et al., 2020). The reason why hybrid models are attracting attention is because once economies are understood to be embedded within wider natural systems, it is no longer possible to retain assumptions about an underlying tendency towards equilibrium. Assumptions about a fundamental underlying tendency towards equilibrium may be appropriate for highly abstract models of economies, but when economies are understood as real-world complex systems rooted within wider social and natural systems, these assumptions become less useful.

Building on the work of SATIM-GE, a novel hybrid model would be essential to advance the modelling of the way energy, climate and economy interact and impact each other. To achieve this would require drawing from international studies (Bovari et al., 2018, 2020; Campiglio et al., 2017; Yilmaz & Godin, 2020). Together these studies have provided a framework for economic-climate modelling and have shown the importance of understanding the relationships between the energy transition and macro-financial and economic dynamics in the context of climate change.

Primary Research Question

In order to appropriately assess the macro-economic and socio-economic implications of increased investments in climate resilient water, energy and food systems, to what extent will the SATIM-GE model need to be augmented with additional modelling dimensions that take into account key drivers like climate change damage factors and finance (specifically debt/GDP ratios)?

Secondary questions:

- What can be learnt from hybrid models that could help augment the SATIM-GE model?
- What are the implications of including a climate change damage factor?
- What are the advantages and disadvantages of including finance?

Research Strategy

The French Development Bank (AFD) has developed advanced capabilities for building hybrid models that include a climate damage factor and financial dynamics. The AFD hybrid modelling team works with several global South countries. Unlike many other similar international initiatives, the AFD's approach is open source and focused on capacity building. It is for this reason that UCT's modelling team has agreed to work with AFD within the SA-TIED framework. A MOU will regulate the roles, activities and IP-related matters involved in this unique research partnership between UCT, AFD, NT and CST.

Based on extensive engagements with the UCT-based modelers responsible for managing the SATIM-GE model, a paper will be compiled that assesses the SATIM-GE model in light of the needs of the WEF CC Workstream. The aim will be to determine whether it is configured appropriately for the purpose of assessing the implications of the water, energy and food challenges in the context of climate change for the evolution of the economy, and therefore the economic policy implications. The paper will assess both the strengths and the weaknesses of the SATIM-GE model given the empirical realities that South Africa faces with respect to water, energy and food supplies. This will provide the basis for making recommendations for how the SATIM-GE might need to be upgraded to handle these realities, or whether a complementary model should be developed.

Conclusion

The scope of research agenda adopted by the WEF CC Workstream goes well beyond a simplistic analysis of the implications of climate change for the water, energy and food sectors. The primary significance of the new and expanding literature on the WEF Nexus is that these three sectors cannot be addressed in isolation from one another. Instead, following the complex adaptive systems logic that underpins the WEF Nexus approach, it is necessary to understand the intersectional dynamics of the way the relations between them evolve in the context of climate change and associated macro-economic impacts. However, to establish a foundation for such an intersectional nexus approach, detailed analyses of the three sectors is required. This is, therefore, the point of departure of the WEF CC Workstream, working in partnership with key public sector institutions and a number of South African Universities.

The terms of reference for the water, energy and food studies as described above prioritizes the investment requirements for achieving the relevant NDP and SDG goals. This financial information will be a key input into the hybrid modelling work that will be required to develop a preliminary assessment of the macro-economic implications of the water-energy-food nexus in the context of climate change that will emerge from the AFD-UCT-CST-NT collaboration. The climate modelling work by the Wits Institute for Global Change will provide the second key input, i.e., a damage factor calculation that becomes an input into the hybrid modelling work.

It needs to be acknowledged that this transdisciplinary research agenda could potentially result in a set of research outputs that not only provide South African policy makers with significant policy-relevant perspectives and decision-support tools, but also contributes to the still nascent by fast-growing global interest in general non-equilibrium hybrid models capable of assessing the macro-economic implications the WEF Nexus in the context of climate change. Furthermore, it will contribute to the still nascent research interest in the governance implications of the WEF Nexus.

References

Albrecht, T.R., Crootof, A. & Scott, C.A. 2018. The Water-Energy-Food Nexus: A systematic review of methods for nexus assessment. *Environmental Research Letters*. 13(4).

Berman, H., Shwom, R. & Cuite, C. 2019. Becoming FEW conscious: A conceptual typology of household behavior change interventions targeting the food-energy-water (FEW) nexus. *Sustainability (Switzerland),* 11(18):5034

Biggs, E., Bruce, E., Boruff, B., Duncan, J.M.A., Horsley, J., Pauli, N., McNeill, K., Neef, A., 2015. Sustainable development and the water-energy-food nexus: A perspective on livelihoods. *Environmental Science and Policy*. 54:389–397.

Biggs, R., Schlüter, M., Biggs, D., Bohensky, E.L., Burnsilver, S., Dakos, V., Daw, T.M., Evans, L.S., Kotschy, K., Leitch, A., Quinlan, A., Raudsepp-hearne, C., Robards, M.D., Schoon, M. L., Schultz, L. & West, P. C. 2012. Towards principles for enhancing the resilience of ecosystem services. *Annual Reviews in Environment and Resources,* 37:421-448.

Biggs, R. Schlüter, M., Schoon, M. L. 2015. Principles for Building Resilience: Sustaining Ecosystems Services in Social- Ecological Systems. Cambridge: Cambridge University Press.

Blanchard, O. 2018. On the future of macroeconomic models. *Oxford Review of Economic Policy*, *34*(1–2), 43–54.

Bolton, P. Depres, M. Pereira da Silva, L.A. Samama, F. Svartzman, R. Banque de France. 2020. The green swan – central banking and financial stability in the age of climate change. [Online]. Available: https://www.bis.org/publ/othp31.pdf [2023, April 2]

Botai, J.O., Tazvinga, H., Botai, C., Ncongwane, K., Murambadoro, M., Mengistu, M.G., Adeola, A.M., Zwane, N., et al. 2023. *From Theory to Practice: Developing a case-study and guidelines for water-energy-food (WEF) nexus implementation in Africa*.

Bovari, E., Giraud, G., & Mc Isaac, F. 2018. Coping With Collapse: A Stock-Flow Consistent Monetary Macrodynamics of Global Warming. *Ecological Economics*, *147*, 383–398.

Bovari, E., Giraud, G., & McIsaac, F. 2020. Financial impacts of climate change mitigation policies and their macroeconomic implications: a stock-flow consistent approach. *Climate Policy*, *20*(2), 179–198.

Burls, N.J., Blamey, R.C., Cash, B.A., Swenson, E.T., Fahad, A.A., Bopape, M.J.M., Straus, D.M. and Reason, C.J., 2019. The Cape Town "Day Zero" drought and Hadley cell expansion. *Npj Climate and Atmospheric Science*, *2*(1):27.

Campiglio, E., Godin, A., Kemp-Benedict, E., & Matikainen, S. 2017. The Tightening Links Between Financial Systems and the Low-Carbon Transition. In A. Philip & M. Sawyer (Eds.), *Economic Policies since the Global Financial Crisis* (1st ed., pp. 313–356). Palgrave Macmillan.

Cohen, S.J. & Allsopp, T.R. 1988. The Potential Impacts of a Scenario of CO2-Induced Climatic Change on Ontario, Canada. Journal of Climate, 1(7):669–681.

Department of Energy. (2019). *Integrated Resource Plan - 2019*. https://cer.org.za/wp-content/uploads/2019/10/IRP-2019_corrected-as-gazetted.pdf [2023, January 12]

Department of Energy (DoE). 2009. *Socio-Economic Impact of Electrification: Household Perspective* [online]. Available: https://www.energy.gov.za/files/media/explained/statistics_households_2001.pdf [2023, April 23]

Department of Environment Forestry and Fisheries (DFFE). (2020). *South Africa's Low Emission Development Strategy (LEDS) 2050.* (Issue February).

Department of Public Works and Infrastructure (DPWI). 2022. *National Infrastructure Plan 2050 (NIP 2050) Phase I.* [Online]. Available: https://www.gov.za/sites/default/files/gcis_document/202203/46033gon1874.pdf [2023, April 25]

Department of Water and Sanitation (DWS). 2022. *Annual Report 2021/2022* [Online]. Available: https://www.gov.za/sites/default/files/gcis_document/202210/dws2021-22annualreport.pdf [2023, April 23]

Department of Water and Sanitation (DWS). 2019. *The national water and sanitation master plan (NW&SMP)* [Online]. Pretoria. Available: https://www.gov.za/sites/default/files/gcis_document/201911/national-water-and-sanitation-master-plandf.pdf [2023, April 10]

Ding, K., Gilligan, J.M. & Hornberger, G.M. 2019. Avoiding "day-zero": A Testbed for Evaluating Integrated Food-energy-water Management in Cape Town, South Africa. In *2019 Winter Simulation Conference (WSC)* (pp. 866-877). IEEE

Directorate: Statistics and Economic Analysis. 2021. *Crops & Markets - Second Quarter* 2021 Volume 102 No. 988 [Online]. Available: http://www.dalrrd.gov.za/phocadownloadpap/Statistics_and_Economic_Analysis/Statistical_Information/Crops and Markets 2nd Quarter 2021.pdf [2023, March 23]

Crookes, C., Hedden, S. and Donnenfeld, Z., 2018. A delicate balance: Water scarcity in South Africa. *ISS Southern Africa Report*, *2018*(13):1-24.

Dumisa, B. 2023. The catastrophic impact of load shedding: Will the economy recover?. *IOL* [Online], 22 January. Available: https://www.iol.co.za/news/politics/opinion/the-catastrophic-impact-of-load-shedding-will-the-economy-recover-0d086bb3-148b-45aa-b525-c92f2f214f95 [2023, March 13]

Engelbrecht, F., Adegoke, J., Bopape, M.J., Naidoo, M., Garland, R., Thatcher, M., McGregor, J., Katzfey, J., Werner, M., Ichoku, C. and Gatebe, C., 2015. Projections of rapidly rising surface temperatures over Africa under low mitigation. *Environmental Research Letters*, *10*(8):085004.

Eskom. 2018. *Water Supply Factsheet* [Online]. Available: https://www.eskom.co.za/wp-content/uploads/2021/03/ENV0001RawWaterSupply.pdf [2023, March 13]

Eskom. 2021a. *Eskom Generation Map* [Online]. Available: https://www.eskom.co.za/wp-content/uploads/2021/04/EskomGenerationDivMapREV81.pdf [2023, March 28].

Eskom. 2021b. *2021 Carbon Footprint Report* [Online]. Available: https://www.eskom.co.za/wp-content/uploads/2022/09/2021-Carbon-Footprint-Report.pdf [2023, March 21]

Eskom. 2022. *Generation Plant Mix* [online]. Available: https://www.eskom.co.za/wp-content/uploads/2022/06/GX-0001-Generation-Plant-Mix-Rev-26.pdf [2023, April 29]

FAO, European Union, CIRAD & DSI-NRF Centre of Excellence in Food Security. 2022. *Food Systems Profile - South Africa: Catalysing the sustainable and inclusive transformation of food systems.* Available: https://doi.org/10.4060/cc0071en. [2023, April 12]

Foley, J.A., DeFries, R., Asner, G.P., Barford, C., Bonan, G., Carpenter, S.R., Chapin, F.S., Coe, M.T., Daily, G.C., Gibbs, H.K., Helkowski, J.K., Holloway, T., Howard, E.A., Kucharik, C.J., Monfreda, C., Patz, J.A., Prentice, I.C., Ramankutty, N. & Snyder, P.K. 2005. Global Consequences of Land Use. *Science,* 309(5734):570–574.

Foran, T. 2015. Node and regime: Interdisciplinary analysis of water-energy-food nexus in the Mekong region. *Water Alternatives,* 8(1):655–674.

GCX 1. 2021. Personal interview. 01 October, Western Cape Economic Development Partnership.

Giraud, G. (2022). Is Sustainability Financially Sustainable? In *SA-TIED Technical Workshop* (pp. 1–59). Southern Africa – Towards Inclusive Economic Development (SA-TIED).

Godin, A. and Yilmaz, S.D., 2020. *Modelling small open developing economies in a financialized world: A stock-flow consistent prototype growth model* (No. 5eb7e0e8-560f-4ce6-91a5-52e5bc819887).

GreenCape. 2022a. *2022 Water Market Intelligence Report* [Online]. Available: https://green-cape.co.za/wp-content/uploads/2022/10/WATER_MIR_30_3_22_FINAL-3.pdf [2023, April 04]

GreenCape. 2022b. *2022 Sustainable Agriculture Market Intelligence Report* [Online]. Available: https://green-cape.co.za/wp-content/uploads/2022/10/AGRI_MIR_29_3_22_FINAL-3.pdf [2023, March 23]

Guild, J. & Shackleton, C. 2018. Informal urban fuelwood markets in South Africa in the context of socio-economic change. *Energy Policy.* 117:136–141.

Hoff, H. 2011. Understanding the Nexus. Background Paper for the Bonn2011 Conference: The Water, Energy and Food Security Nexus. Stockholm Environment Institute (SEI), Stockholm, Sweden [Online] Available: https://mediamanager.sei.org/documents/Publications/SEI-Paper-Hoff-UnderstandingTheNexus-2011.pdf [2021, March 14]

IEA, IRENA, UNDS, The World Bank & WHO. 2022. *Tracking SDG7 - The Energy Progress Report 2022* [Online]. Available: https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2022/Jun/SDG7_Tracking_Progress_2022.pdf?rev=fbde91b736274cee985e00696df60cb4. [2023, March 13]

Institut Rousseau. 2022. *2% for 2°C!* [Online]. 8 March. Available: https://institut-rousseau.fr/2-pour-2c-resume-executif/ [2023, January 18]

IPBES. 2019. *Global assessment report on biodiversity and ecosystem services of the Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services*. Brondizio, E. S., Settele, J., Diaz, S., Ngo, H. T. (eds). IPBES secretariat, Bonn, Germany. 1144 pages. ISBN: 978-3-947851-20-1

Integrated Food Security Phase Classification (IPC). 2021. IPC Acute Food Insecurity Analysis - South Africa September 2020-March 2021 [Online]. Available: https://www.ipcinfo.org/fileadmin/user_upload/ipcinfo/docs/IPC_South_Africa_AcuteFoodInsec_2020Nov2021Mar_Report.pdf [2023, March 12]

IPCC. 2021. Climate change widespread, rapid, and intensifying [Press release]. Geneva. 9 August. Available: https://www.ipcc.ch/site/assets/uploads/2021/08/IPCC_WGI-AR6-Press-Release_en.pdf [2023, April 29]

IPCC. 2022. *Climate Change 2022: Impacts, Adaptation, and Vulnerability*. H.-O. Pörtner, D.C. Roberts, M. Tignor, E.S. Poloczanska, K. Mintenbeck, A. Alegria, M. Craig, S. Langsdorf, S. Löschke, V. Möller, A. Okem, & B. Rama, Eds. Cambridge: Cambridge University Press. Available: https://www.ipcc.ch/report/sixth-assessment-report-working-group-ii/ [2022, August 03].

IRP. 2019. Global Resources Outlook 2019: Natural Resources for the Future We Want. Oberle, B.,Bringezu, S., Hatfield-Dodds, S., Hellweg, S., Schandl, H., Clement, J., and Cabernard, L., Che, N., Chen, D., Droz-Georget , H., Ekins, P., Fischer-Kowalski, M., Flörke, M., Frank, S., Froemelt , A., Geschke, A., Haupt , M., Havlik, P., Hüfner, R., Lenzen, M., Lieber, M., Liu, B., Lu, Y., Lutter, S., Mehr , J., Miatto, A., Newth, D., Oberschelp , C., Obersteiner, M., Pfister, S., Piccoli, E.,

IRP. 2017. Green Technology Choices: The Environmental and Resource Implications of Low-Carbon Technologies. Suh, S., Bergesen, J., Gibon, T. J., Hertwich, E., Taptich M. A report of the International Resource Panel. United Nations Environment Programme, Nairobi, Kenya.

Kaddoura, S. & Khatib, S.E. 2017. Review of water-energy-food Nexus tools to improve the Nexus modelling approach for integrated policy making. *Environmental Science & Policy*. 77:114–121.

Karekezi, S., McDade, S., Boardman, B., Kimani, J. & Lustig, N. 2012. Energy, Poverty, and Development. *In Global Energy Assessment: Toward a Sustainable Future.* Global Energy Assessment Writing Team, Ed. Cambridge: Cambridge University Press. 151–190.

Katz, S. L., Padowski, J.L., Goldsby, M., Brady, M.P., & Hampton, S.E. 2020. Defining the Nature of the Nexus: Specialization, Connectedness, Scarcity, and Scale in Food–Energy– Water Management. *Water,* 12(4):972

Kruger, A.C. and Nxumalo, M.P., 2017. Historical rainfall trends in South Africa: 1921–2015. *Water SA*, *43*(2):285-297.

Kruger, A.C. and Sekele, S.S., 2013. Trends in extreme temperature indices in South Africa: 1962–2009. *International Journal of Climatology*, *33*(3):661-676.

Kruger, A.C. and Shongwe, S., 2004. Temperature trends in south africa: 1960–2003. *International Journal of Climatology: A Journal of the Royal Meteorological Society*, *24*(15):1929-1945.

Laspidou, C.S., Mellios, N.K., Spyropoulou, A.E., Kofinas, D.T. & Papadopoulou, M.P. 2020. Systems thinking on the resource nexus: Modeling and visualisation tools to identify critical interlinkages for resilient and sustainable societies and institutions. *Science of the Total Environment*. 717.

Lawford, R., Bogardi, J., Marx, S., Jain, S., Wostl, C.P., Knüppe, K., Ringler, C., Lansigan, F., et al. 2013. Basin perspectives on the Water-Energy-Food Security Nexus. *Current Opinion in Environmental Sustainability.* 5(6):607–616.

Luo, T., Young, R. & Reig, P. 2015. Aqueduct Projected Water Stress Country Rankings. *Technical Note*, *16*.

Mabhaudhi, T., Nhamo, L., Mpandeli, S., Nhemachena, C., Senzanje, A., Sobratee, N., Chivenge, P.P., Slotow, R., et al. 2019. The Water-Energy-Food Nexus as a Tool to Transform Rural Livelihoods and Well-Being in Southern Africa. *Int. J. Environ. Res. Public Health*. 16:2970.

Mabhaudhi, T., Mpandeli, S. & Nhamo, V.G.L. 2020. Emerging water-energy-food nexus lessons, experiences, and opportunities in southern Africa. In *Environmental Management of Air, Water, Agriculture, and Energy* (pp. 141-158). CRC Press.

MacKellar, N., New, M. and Jack, C., 2014. Observed and modelled trends in rainfall and temperature for South Africa: 1960-2010. *South African Journal of Science*, *110*(7-8):1-13.

Macmillan-Scott, E., Stodulka, K., Meldrum, M., Kennedy, M., Swilling, M., Callaghan, N., Mohlakoana, N., & Johnson, E. 2022. *Making Climate Capital work: Unlocking $8.5bn for South Africa's Just Energy Transition With thanks to*. https://www.markswilling.co.za/wp-content/uploads/2022/06/MakingClimateCapitalWork-FINALREPORT.pdf [2023, April 3]

Märker, C., Venghaus, S. & Hake, J.F. 2018. Integrated governance for the food–energy–water nexus – The scope of action for institutional change. *Renewable and Sustainable Energy Reviews*, 97:290–300.

Martin-Nagle, R., Howard, E., Wiltse, A. & Duncan, D. 2012. Conference Synopsis. Bonn2011 Conference: The Water, Energy and Food Security Nexus Solutions for the Green Economy 16 – 18 November 2011 [Online]. Available: https://www.water-energy- food.org/news/bonn2011-nexus-conference-bonn2011-conference-synopsis [2020, 04 March].

Mbokodo, I., Bopape, M.J., Chikoore, H., Engelbrecht, F. and Nethengwe, N., 2020. Heatwaves in the future warmer climate of South Africa. *Atmosphere*, *11*(7):712.

McKay, D.I.A, Staal, A., Abrams, J.F., Winkelmann, R., Sakschewski, B., Loriani, S., Fetzer, I., Cornell, S.E., Rockström, J. and Lenton, T.M., 2022. Exceeding 1.5 C global warming could trigger multiple climate tipping points. *Science*, *377*(6611), p. eabn7950.

Merven, B., Hartley, F., Marquard, A., Ahjum, F., Burton, J., Hughes, A., Mccall, B. & Schers, J. 2021. *Climate mitigation in South Africa*. Working Paper no. 174. United Nations University [online]. Available: https://sa-tied.wider.unu.edu/sites/default/files/SA-TIED-WP174.pdf [2023, April 26]

Merven, B. 2020. *An overview of SATIMGE: a linked Energy-Economic model for South Africa* (pp. 1–38). University of Cape Town.

Merven, B., Hartley, F., Mccall, B., Burton, J., & Schers, J. 2019. Improved representation of coal supply for the power sector for South Africa Working Paper No. 84. SA-TIED[Online]. Available: https://sa-tied.wider.unu.edu/sites/default/files/pdf/SATIED_WP84_Merven_Hartley_McCall_Burton_Schers_October_2019.pdf [2023, March 14]

Merven, B., Hartley, F. and Arndt, C., 2019. Quantifying the macro-and socio-economic benefits of a transition to renewable energy in South Africa. *GTAP Conference paper*. 15 April 2019, Warsaw, Poland [Online]. Available: https://www.gtap.agecon.purdue.edu/resources/res_display.asp?RecordID=5829

Merven, B., Ireland, G., Hartley, F., Arndt, C., Hughes, A., Ahjum, F. & Caetano, T. 2018. Quantifying the macro- and socio-economic benefits of a transition to renewable energy in South Africa. Working Paper No. 26. United Nations University [online]. Available: https://sa-tied.wider.unu.edu/sites/default/files/pdf/WP-19-2018-Merven.pdf [2023, March 12]

Mguni, P. & van Vliet, B.J.M. 2021. Rethinking the urban Nexus - Resilience and vulnerability at the urban Nexus of Water, Energy and Food (WEF). An introduction to the special issue. *Journal of Integrative Environmental Sciences*, 17(2):i-v

Mpandeli, S., Naidoo, D., Mabhaudhi, T., Nhemachena, C., Nhamo, L., Liphadzi, S., Hlahla, S. & Modi, A.T. 2018. Climate Change Adaptation through the Water-Energy-Food Nexus in Southern Africa. *Int. J. Environ. Res. Public Health.* 15:2306.

Naidoo, D., Nhamo, L., Mpandeli, S., Sobratee, N., Senzanje, A., Liphadzi, S., Slotow, R., Jacobson, M., et al. 2021. Operationalising the water-energy-food nexus through the theory of change. *Renewable and Sustainable Energy Reviews.* 149:111416.

Namany, S., Al-Ansari, T. & Govindan, R. 2019. Sustainable energy, water and food nexus systems: A focused review of decision-making tools for efficient resource management and governance. *Journal of Cleaner Production.* 225:610–626.

National Business Initiative (NBI). 2022. *Financing South Africa's Just Transition*.

National Planning Commission (NPC). 2012. *National Development Plan 2030: Our future - Make it work*. https://www.gov.za/sites/default/files/gcis_document/201409/ndp-2030-our-future-make-it-workr.pdf [2023, March 12]

Ndovela, M. 2023. The Economics of Climate Change in Integrated Assessment Models: The Damage Function Dilemma. In *Risk and Uncertainty in Finance and Economics Conference* (pp. 1–4). University of Johannesburg.

Newell, J.P., Goldstein, B. & Foster, A. 2019. A 40-year review of food-energy-water nexus literature and its application to the urban scale. Environmental Research Letters. 14(7).

News24. 2023. *Load shedding costs SA R900m a day, says Reserve Bank* [Online]. 06 February. Available: https://www.news24.com/fin24/economy/load-shedding-costs-sa-r900m-a-day-says-reserve-bank-20230206 [2023, March 27]

Nhamo, L., Mabhaudhi, T., Mpandeli, S., Dickens, C., Nhemachena, C., Senzanje, A., Naidoo, D., Liphadzi, S., et al. 2020. An integrative analytical model for the water-energy-food nexus: South Africa case study. *Environmental Science and Policy*. 109:15–24.

Nicholls, S. 2022. Carbon budgets and the implications for economic transition in South Africa. In *The strengths and limitations of long-term structural models: DSGE, CGE, Energy-Economic (SATIM-GE) and hybrid models* (pp. 1–23).

Opejin, A.K., Aggarwal, R.M., White, D.D., Jones, J.L., Maciejewski, R., Mascaro, G. & Sarjoughian, H.S. 2020. A bibliometric analysis of food-energy-water nexus literature. *Sustainability (Switzerland).* 12(3):1–18.

Peng, P., Ren, X., Zhu, L., Fan, Y. and Massimo, T., 2019. A Comparison of Two Approaches for Damage Evaluation on Optimal Mitigation and Adaptation Responses in China. *Journal of Systems Science and Complexity*, *32*(6):641-1658.

Presidential Climate Commission (PCC). 2022. *A Presidential Climate Commission Report: A Framework for a Just Transition in South Africa*. https://pccommissionflow.imgix.net/uploads/documents/A-Just-Transition-Framework-for-South-Africa-with-dedication-FSP-002.pdf

Republic of South Africa. 2021. *First Nationally Determined Contribution Under the Paris Agreement* [Online]. Available: https://unfccc.int/sites/default/files/NDC/2022-06/South%20Africa%20updated%20first%20NDC%20September%202021.pdf [2023, March 12]

Republic of South Africa. 2022. *Official Guide to South Africa 2021/2022*. Available: https://www.gcis.gov.za/sites/default/files/24 Water and Sanitation 2021-22.pdf [2023, April 18]

Roffe, S.J., Fitchett, J.M. & Curtis, C.J. 2021. Investigating changes in rainfall seasonality across South Africa: 1987–2016. *International Journal of Climatology*. 41(S1): E2031–E2050.

Salam, P.A., Shrestha, S., Pandey, V.P. and Anal, A.K. eds., 2017. *Water-energy-food nexus: Principles and practices* (Vol. 229). John Wiley & Sons.

Schaldach, R., Schüngel, J., Sonderegger, T., Sudheshwar, A., Tanikawa, H., van der Voet, E., Walker, C., West, J., Wang, Z., Zhu, B. A Report of the International Resource Panel. United Nations Environment Programme. Nairobi, Kenya.

Schlör, H., Venghaus, S. & Hake, J.F. 2018. The FEW-Nexus city index – Measuring urban resilience. *Applied Energy*, 210(C):382–392.

Selomane O. and Reyers B. 2020. "Pathways to Sustainable Land-Use and Food Systems in South Africa by 2050" In: FABLE 2020, *Pathways to Sustainable Land-Use and Food Systems,* 2020 Report of the FABLE Consortium. Laxenburg and Paris: International Institute for Applied Systems Analysis (IIASA) and Sustainable Development Solutions Network (SDSN), pp. 568-594.

Serrano-Tovar, T., Suárez, B.P., Musicki, A., de la Fuente Bencomo, J.A., Cabello, V. & Giampietro, M. 2019. Structuring an integrated water-energy-food nexus assessment of a local wind energy desalination system for irrigation. *Science of the Total Environment.* 689:945–957.

Shepherd, N. 2019. Making Sense of "Day Zero": Slow Catastrophes, Anthropocene Futures, and the Story of Cape Town's Water Crisis. *Water,* 11(9):1744.

Simpson, G. 2020. The development of the Water-Energy-Food Nexus Index and its application to the Southern African Development Community. University of KwaZulu-Natal.

Smajgl, A., Ward, J. & Pluschke, L. 2016. The water-food-energy Nexus - Realising a new paradigm. *Journal of Hydrology*, 533:533–540.

Southern Africa – Towards Inclusive Economic Development (SA-TIED). [online]. [n.d.] Available: https://sa-tied.wider.unu.edu/about [2023, April 18]

South Africa Government. 2012. *South Africa's Constitution of 1996 with Amendments through 2012*, 1. (Testimony of South African Government) [Online]. Available: https://www.constituteproject.org/constitution/South_Africa_2012.pdf?lang=en [2023, April 10]

StatsSA. 2023. *GDP declines in the fourth quarter* [Online]. Available: https://www.statssa.gov.za/?p=16162. [2023, April 18]

Stirling, A. 2015. *Developing 'Nexus Capabilities': towards transdisciplinary methodologies* [Online]. Available: https://thenexusnetwork.org/wp-content/uploads/2015/06/Stirling-2015-Nexus-Methods-Discussion-Paper.pdf. [2023, 18 April]

Sustainable Energy Africa. 2014. *Tackling Urban Energy Poverty in South Africa* [Online]. Available: https://www.sustainable.org.za/uploads/files/file72.pdf. [2023, March 13]

Swart, L. 2023. Exploring the practical, social, and governance realities of a Water- Energy-Food (WEF) Nexus Governance approach: A case study of the V&A Waterfront in Cape Town, South Africa. Unpublished master's thesis. Stellenbosch: Stellenbosch University.

Swilling, M. 2022, October 7. *Reflections on a Missing Link: Finance, Justice, and Sustainability Transitions* (pp. 1–18). Environmental Justice Programme, Georgetown University [Video file]. Available: https://www.youtube.com/watch?v=2x-KRZ9xqO0 [2023, April 13]

Swilling, M. 2020. *The Age of Sustainability: Just Transitions in a Complex World*. London & New York: Routledge

The Presidency. (2022). *South Africa's Just Energy Transition Investment Plan (JET IP)*.

United Nations Environment Programme (UNEP). 2015. *Options for decoupling economic growth from water use and water pollution.* Report of the International Resource Panel Working Group on Sustainable Water Management.

United Nations Environment Programme (UNEP). 2011. *Decoupling natural resource use and environmental impacts from economic growth, A Report of the Working Group on Decoupling to the International Resource Panel*. Fischer-Kowalski, M., Swilling, M., von Weizsäcker, E.U., Ren, Y., Moriguchi, Y., Crane, W., Krausmann, F., Eisenmenger, N., Giljum, S., Hennicke, P., Romero Lankao, P., Siriban Manalang, A., Sewerin, S.

United Nations Framework Convention on Climate Change (UNFCCC). 2016. *Report of the Conference of the Parties on its twenty-first session. 30 November to 13 December 2015, Paris* [Online]. Available: https://unfccc.int/resource/docs/2015/cop21/eng/10a01.pdf

United Nations Framework Convention on Climate Change (UNFCCC). 2020. *South African Emission Development Strategy 2050* [Online]. Available: https://unfccc.int/sites/default/files/resource/South%20Africa%27s%20Low%20Emission%20Development%20Strategy.pdf [2023, January 12]

United Nations Framework Convention on Climate Change (UNFCCC). 2021, April 15. *What is the Kyoto Protocol?* [Online]. Available: https://unfccc.int/kyoto_protocol [2023, March 29]

Urbinatti, A.M., Benites-Lazaro, L.L., de Carvalho, C.M. & Giatti, L.L. 2020. The conceptual basis of water-energy-food nexus governance: Systematic literature review using network and discourse analysis. *Journal of Integrative Environmental Sciences*, 17(2):21–43.

V&A 1. 2021. Personal interview. 10 November, V&A Waterfront.

V&A 2. 2022. Personal interview. 23 February, V&A Waterfront.

V&A 3. 2022. Personal interview. 12 April, V&A Waterfront.

V&A Waterfront. 2022a. Sustainability Overview [Online]. Available: https://www.waterfront.co.za/the-va/sustainability/ [2021, January 01].

Vandentorren, S., Bretin, P., Zeghnoun, A., Mandereau-Bruno, L., Croisier, A., Cochet, C., Ribéron, J., Siberan, I., Declercq, B. and Ledrans, M., 2006. August 2003 heat wave in France: risk factors for death of elderly people living at home. *The European Journal of Public Health*, *16*(6):583-591.

Wagenaar, H. & Wilkinson, C. 2015. Enacting Resilience: A Performative Account of Governing for Urban Resilience. *Urban Studies*, 52(7):1265–1284.

Waggoner, P.E. 1983. Agriculture and a Climate Changed by More Carbon Dioxide. Changing Climate. National Academy Press, Washington DC, 383-418.

Weitz, N., Strambo, C., Kemp-Benedict, E. & Nilsson, M. 2017. Closing the governance gaps in the water-energy-food nexus: Insights from integrative governance. *Global Environmental Change*, 45(June):165–173.

Wichelns, D. 2017. The water-energy-food nexus: Is the increasing attention warranted, from either a research or policy perspective? *Environmental Science and Policy*. 69:113–123.

World Bank. 2023. *GDP (current US$) - South Africa*. Data Bank. March 1 [Online]. Available: https://data.worldbank.org/indicator/NY.GDP.MKTP.CD?locations=ZA [2023, March 30]

World Bank. 2022. *Country Climate and Development Report: South Africa* [Online]. Available: https://openknowledge.worldbank.org/entities/publication/c2ebae54-6812-51d3-ab72-08dd1431b873 [2023, February 10]

World Economic Forum. 2021. Circular Cities: A circular water economy for cleaner, greener, healthier, more prosperous cities. *Briefing Paper. 16.* Available: https://www3.weforum.org/docs/WEF_Imagine_IF_Water-Series_2021.pdf [2023, March 11]

WorldOMeter. 2016. CO2 *Emissions by Country* [Online]. Available: https://www.worldometers.info/co2-emissions/co2-emissions-by-country/ [2023, March 27].

Ye, Y., Koch, S.F. & Zhang, J. 2018. Determinants of household electricity consumption in South Africa. *Energy Economics*. 75:120–133.

Yilmaz, S.-D., & Godin, A. (2020). *Modelling Small Open Developing Economies in a Financialized World: A Stock-Flow Consistent Prototype Growth Model*.

Zhang, T., Tan, Q., Yu, X. and Zhang, S., 2020. Synergy assessment and optimization for water-energy-food nexus: Modeling and application. *Renewable and Sustainable Energy Reviews*, 134:110059.