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A review of energy systems and economic modelling tools capable of estimating the finance needs and responses relevant to energy, water, and food security in South Africa in the face of climate change

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About the project

Southern Africa – Towards Inclusive Economic Development (SA-TIED)

SA-TIED is a unique collaboration between local and international research institutes and the government of South Africa. Its primary goal is to improve the interface between research and policy by producing cutting-edge research for inclusive growth and economic transformation in the southern African region. It is hoped that the SA-TIED programme will lead to greater institutional and individual capacities, improve database management and data analysis, and provide research outputs that assist in the formulation of evidence-based economic policy.

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Abstract: This paper reviews the extent of hybrid energy- and climate-economy modelling within South Africa. Only a small number of hybrid climate-economy models exist, with SATIMGE being the most developed model of this type used for South Africa. SATIMGE is reviewed with respect to its potential usefulness and limitations for estimating finance needs to ensure not only energy, but also water and food security in the face of a warming climate.

SATIMGE is highly developed to evaluate energy mitigation policy. However, it lacks detail on physical climate damage risk and financial dynamics of the economy and has no spatial resolution. Considering climate and financial risk is crucial for assessing the macroeconomic and socioeconomic implications of climate-resilient systems. Improving spatial resolution in modelling tools can enhance accuracy in climate-economy assessments. The paper will examine the SATIMGE model and propose advancements in South African climate-economy modelling, including consideration of financial dynamics, climate impacts, and spatial detail.

Key words: energy, climate, finance, hybrid modelling, WEF nexus, damage factor

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Acronyms and abbreviations

AFD	Agence Française de Développement
CGE	Computable general equilibrium
DoE	Department of Energy
DFFE	Department of Forestry, Fisheries and the Environment
DME	Department of Minerals and Energy
DMRE	Department of Mineral Resources and Energy
GDP	Gross domestic product
GHG	Greenhouse gas
IAM	Integrated assessment model
JET	Just energy transition
NDC	Nationally determined contribution
SACRED	System Assessment of Climate Change Resilient Development
SAM	Social accounting matrix
SAGE	South African General Equilibrium
SARB	South African Reserve Bank
SATIM	South African Times Model
TIPS	Trade & Industry Policy Strategies
WEF	Water, energy, and food

1 Background: climate change and the WEF

The water-energy-food (WEF) nexus concept provides a holistic framework to study and address the interconnections and interdependencies among water, energy, and food systems. The WEF nexus views water security, food security, and energy security as linked to one another, meaning any policy action in one of the three sectors often has an impact on the two other sectors. Research on the water, energy, food nexus arose in response to criticism on the traditional methods used to manage resource development. It is often the case that planning for research development takes place in isolation. An isolated approach does not fully consider the trade-offs and interactions between resource systems. The WEF nexus approach proposes an organized co-management of the WEF system with collaboration and coordination from different sectors (Swilling et al. 2024. Climate change poses a major threat to the balance of the WEF nexus which will occur across a range of spatial and temporal scales. When planning for the impact of climate change and weighing up different mitigation and adaption policies across these three sectors, context is critical, and this is often achieved by working at a regional (sub-national), water catchment, or city scale (Ding et al. 2021).

It is estimated that the effects of climate change will be predominantly felt through the water sector. South Africa is in general a water-scarce country, and climate change poses a significant threat to water security. Many parts of South Africa have been frequently affected by droughts in the last four decades, with particularly severe and persistent drought conditions impacting parts of the Northern Cape, Eastern Cape, and Western Cape, resulting in a state of disaster being declared in 2021. Droughts and rainfall patterns are likely to be increasingly variable, thus affecting the supply of clean, fresh water. South Africa's already stressed water situation will be put under more pressure by urban migration and aging infrastructure.

The energy sector in South Africa is severely supply constrained, with load shedding reaching its highest recorded levels in 2023 with 6,947 hours of load shedding.[1] Several studies have tried to estimate the macroeconomic impact of load shedding on the South African economy with highly variable results, however, there is board consensus that high levels of load shedding have significantly adverse effects on economic growth and employment (Bhorat and Köhler 2024; SARB 2023). The South African energy sector has started to transition from a heavy reliance on coal, with this source providing 80% of electricity in 2022 (Pierce and Le Roux 2022), down from over 90% a decade earlier. The nationally determined contribution (NDC) under the Paris Agreement seeks to significantly reduce emissions and align with international goals to limit warming to well below 2°C. Coal-fired electricity generation has a significant water intensity, accounting for 2% of South Africa's water withdrawals (ASSAf 2023).

In the context of South Africa being in general a water-scarce region, the largest use (60%) of abstracted water in South Africa is for agriculture and food production (Cammarano et al. 2020). Agriculture contributes significantly to livelihoods and local economies; it is considered central to the economy, forming the basis for food

[1] See https://loadshed.theoutlier.co.za/.

production. The agriculture sector is also one of the most unequal sectors in South Africa, with varying degrees of vulnerability depending on the relative ability to adapt to the climate crisis. The level of adaptation required in the agricultural sector will depend on the severity of climate impacts in specific regions, as well as governance and planning. Climate-induced change in water availability is likely to have the most immediate and significant impact. The persistent drought in numerous regions of South Africa continues to significantly affect the viability of numerous farms. Farmers in the Northern Cape, Western Cape, and Eastern Cape remain vulnerable to the continuing drought conditions (Mogoatlhe 2022). Crop yield will also be impacted by increasing temperatures. Currently, there is enough food production in South Africa to feed the entire country, however, 30% of South Africans are food insecure. This is due to high levels of poverty as food security in South Africa is more a function of income then food availability. However, a reduction in agricultural output due to climate change is likely to have an impact on food prices which could exacerbate food insecurity for poor households.

While South Africa's power sector is water intensive, it does not include the running of large hydro power plants nor is it likely to in the future. Therefore, there is no major trade-off between using water for energy production versus agriculture. Instead, the major trade-off in the WEF nexus is how to distribute the limited funds available for investment in mitigation in the energy sector versus adaptation to build climate-resilient water and agriculture systems. The WEF nexus involves critical infrastructure which may face increased stress due to changing water availability, extreme weather events, or sea-level rise. Policy makers must understand the trade-offs between investment options in these three sectors.

2 Purpose and scope

This paper provides a review of the extent of energy and climate economic modelling within South Africa. There are a several tools which have been used to model the South African energy system which range from detailed power-sector-specific models to fully developed economy-wide models. Only a small number of hybrid climate-economy models exist. The SATIMGE energy-economy model is the most-developed hybrid model of this type for South Africa and has been used to evaluate the mitigation investment needs to achieve the energy transition. SATIMGE does not include detail into the financial dynamics of the economy, climate damage factors and has no spatial resolution.

Climate and financial risk are both important when trying to appropriately assess the macro-economic and socio-economic implications of increased investment in climate-resilient water, energy, and food systems. The spatial resolution of modelling tools is another factor that can significantly add to the accuracy of climate-economy models attempting to assess these outcomes. This paper will review the SATIMGE model and evaluate how South African climate-economy modelling could be advanced considering financial dynamics, expected climate impacts, and the importance of spatial detail.

3 Classifying energy economic models

This analysis will go through some of the main criteria outlined in the literature that have been applied to energy-economic models. There are two distinct modelling approaches in the literature which define the level of technological detail in energy-economic models. The level of technological explicitness is defined by whether a model is top-down (low levels of technological detail) or bottom-up (high levels of technological detail) (Lefevre 2016; Scrieciu et al. 2013). Models are often defined by their model solution approach, which considers whether a model uses simulation or optimization methods. Hybrid models can be classified by the strength of their integration which describes how two separate models are linked. There has also been debate around how to treat technological change and whether models endogenize part of the technological process (Lefevre 2016; Rivers and Jaccard 2006).

Doukas et al. (2019) classify five general energy-economic model structures which distinguish models by how the economy is modelled and the way other models are integrated. These are optimal growth integrated assessment models (IAMs), general equilibrium models, partial equilibrium models, macro-econometric models, and other integrated assessment models. The level of disaggregation between these different classifications of economic models varies significantly. Therefore, models are often categorized by their level of economic (mono economy or multisectoral models) and spatial (global, national, regional) disaggregation.

3.1 Simulation versus optimization

Economic optimization models are generally positioned under economic theories of optimal growth and equilibrium. They typically take on the form of general equilibrium models or optimal growth models (Scrieciu et al. 2013). General equilibrium models are generally based on the assumption of full employment, where equilibrium can be achieved through price adjustments and market clearing.

Simulation models try to offer a more accurate representation of how the economy and energy systems operate by depicting them as suboptimal, non-equilibrium processes. Within these models, there is a restricted ability to predict the future, and resources may not always be fully utilized or employed optimally in the baseline scenario. Simulation models employed for climate policy analysis typically encompass macro econometric models, agent-based models, and certain input–output models. These models aim to capture the dynamic and sometimes unpredictable behaviour of economic and energy systems, providing insights into the potential consequences of climate policies under more realistic conditions (Scrieciu et al. 2013).

Simulation models diverge from optimization models in that they do not seek to optimize a specific objective function. Instead, they depict multiple interconnected energy-emissions–economic relationships. Drawing from historical observations, simulation models aim to forecast the performance of a given system. Optimization models, on the other hand, strive to find the optimal design for a system. These models operate under the assumption of an economy in equilibrium, following an optimal trajectory. Simulation models implicitly assume path dependency, suggesting that historical trends significantly influence outcomes, and they underscore the pivotal role of macroeconomic policies in altering the existing status quo.

3.2 Hybrid model integration

Hybrid models often integrate separate existing top-down and bottom-up models, therefore hybrids can fall across multiple model criteria. The way in which hybrid models integrate bottom-up and top-down models has been defined in the literature and become another way to group hybrid climate-economy models (Lefevre 2016). Hybrid models can create links (soft links) between two separate models or can be a single model that either contains one reduced-form model within another or fully integrates two separate models (Böhringer and Rutherford 2008; Lefevre 2016).

In the case where a singular model is developed, the level of integration is described as 'weak' integration when the integration is completed with a reduced-form representation of the original models (Böhringer and Rutherford 2008). These models have also been referred to as 'pseudo-hybrid' models. The degree of integration in the second case of fully integrated hybrid models is referred to as 'strong integration' or 'hard linked' hybrid models (Lefevre 2016). In this case both the technical detail and economic richness of two separate models is captured in one single format.

Technological change

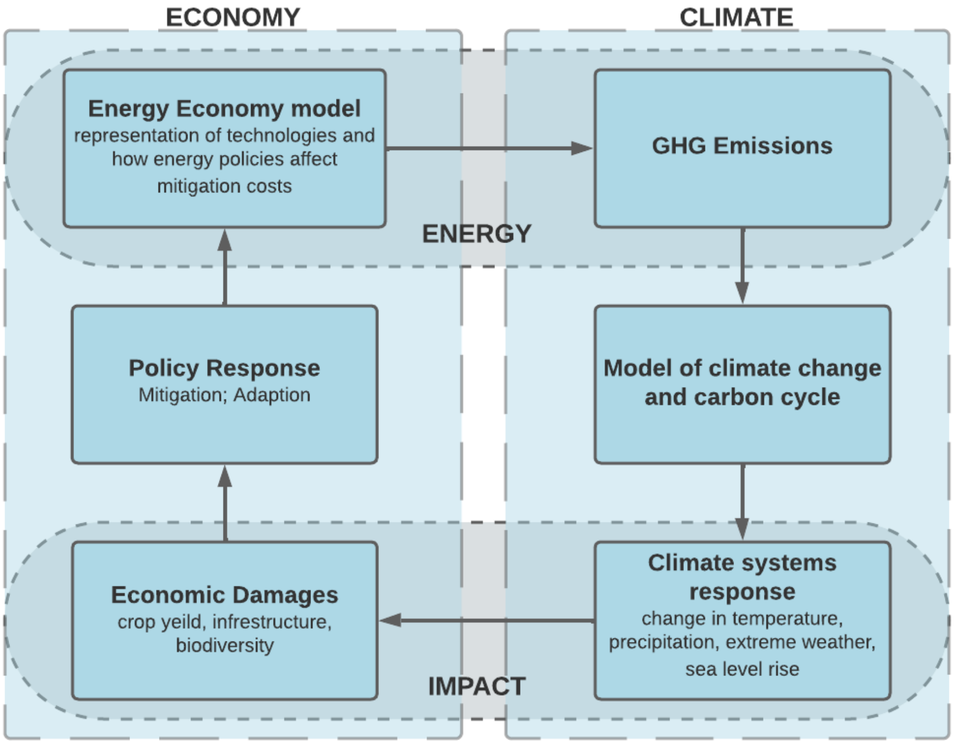
Models are often grouped by how technological change is treated. There is debate in the literature on whether technological change should be considered an exogenous process. Endogenous technological change recognizes that technological change is not solely an exogenous process and is partly endogenous to the economic and political context. Therefore, some models include endogenous technological change and make the technological process dependent on economic variables such as price signals, research and development investment, or cumulative production (Lefevre 2016).

3.3 Optimal growth and integrated assessment models (IAMs)

Optimal growth models or welfare optimization IAMs are often relatively simple representations of economies compared to other classifications. IAMs can be defined as models that integrate knowledge from two or more domains into a single framework (Nordhaus 2019). Figure 1 below depicts the climate-economy dynamics of generic IAMs, identifying four key domains of climate-economy modelling.

Optimal growth models are typically formulated as top-down mono-sectoral optimization models, representing the economy as a single all-encompassing sector. They are designed to determine climate policy and investment levels that maximize social welfare where social welfare is defined as the utility of the representative agent in an economy (Nikas et al. 2018). The spatial resolution of these models is generally very coarse, and they are often formulated as global climate models. The dynamic integrated climate economy (DICE) model and regional integrated climate economy (RICE) model structures are the most prominent and widely used models of this type (Scrieciu et al. 2013).

Figure 1: Climate-economy dynamics with four domains—economy, energy, climate, and impact



Source: adaption of Figure1 in and Doukas et al. (2019:3), which is under Creative Commons Attribution 4.0 International License; with additional information found Anvari et al. (2022).

3.4 Partial equilibrium models

Partial equilibrium models typically focus on a particular sector and operate under the assumption that prices in the remainder of the economy will remain unchanged. These models are considered suitable when the analysed disturbances predominantly influence one market and are expected to have a restricted impact on the overall economy. They are commonly utilized to evaluate potential climate-related damage to sectors. While partial equilibrium models offer detailed insights into the consequences for specific sectors compared to general equilibrium models, they neglect to consider how a disruption in one sector could impact the broader economy. One of the initial applications of partial equilibrium models was to assess the implications of climate change on the agricultural sector (Nikas et al. 2018).

Energy systems models

Energy systems models fall under the umbrella of partial equilibrium models, with a specific focus on the energy sector. These models make up a significant portion of partial equilibrium or bottom-up models. Analysing climate and energy policies demands a level of granularity that surpasses the conventional top-down modelling approach. Bottom-up technology-focused energy system models offer the necessary detail in the energy sector to effectively assess the impacts of energy policy. Often, energy systems models are integrated with computable general equilibrium (CGE) or macroeconomic models to complement the insights provided by the top-down approach.

Energy systems models can broadly be categorized into optimization and simulation models. Optimization models utilize information on prices and technical constraints to identify the optimal or least-cost technology. They assume rational behaviour from consumers and allocate energy suppliers accordingly. Optimization models can determine the least-cost pathways while adhering to emission constraints. On the other hand, simulation models aim to capture technological and economic dynamics to achieve realism. Unlike optimization models, they focus on the most probable outcome based on empirical observations, acknowledging that producers and consumers may act with objectives that differ from optimization models (Nikas et al. 2018).

There are five key energy systems frameworks or tools that are used in South Africa, these are PLEXOS, PyPSA-ZA, TIMES, OSeMOSYS, and LEAP (Anvari et al. 2022; Taviv and Mapako 2008). PyPSA-ZA and PLEXOS are power-sector-only optimization tools. The South African TIMES model (SATIM) and OSeMOSYS are full-sector optimization models of the South African energy system. LEAP is an energy simulation model platform, which has been used for South Africa to represent energy demand, energy transformation, and resources (Taviv and Mapako 2008), and more recently for a study on the effect of household appliance energy efficiency standards on total residential power demand (Hughes and Larmour 2021). CIMS is a hybrid simulation model which looks at the interaction of energy supply and economic performance (Rivers and Jaccard 2006)

3.5 General equilibrium models

General equilibrium models, including computable general equilibrium (CGE) models, offer a more intricate depiction of the economy, encompassing multiple sectors with higher sectoral resolution compared to optimal growth models(Doukas et al. 2019). These models enable a more comprehensive analysis by capturing the dynamics of a real market economy, where interactions among households and producers drive price adjustments and behavioural changes, which are endogenous (Anvari et al. 2022). Consumer utility maximization and producer profit maximization shape the emergence of demand and supply within CGE models. Characterized by strong ties to climate and energy studies, CGE models stand as the most sophisticated tools for evaluating climate policies (Lefevre 2016).

They are algebraic representations of market economy operations, rooted in the abstract theoretical framework governing decentralized economy pricing mechanisms. Referred to as computable models, they utilize economic data to derive numerical parameters that simulate real-world scenarios when equilibrium prices are solved for. National accounts furnish data on goods and services expenditure by production sectors and households, while additional data on demand and supply elasticities, imports/exports, and factor substitution is also required. These parameters are calibrated to ensure that the numerical model’s equilibrium solution replicates real economy data for a specified year. A key advantage of CGE models lies in their ability to not only track the effects of a policy or shock on one sector but also to trace its broader impact on other sectors, changes in consumption, and welfare effects. This capacity for equilibrium feedback sets CGE models apart from partial equilibrium models, which focus on specific sectors, and other models lacking detailed multisectoral representations of the economy. Additionally, the theoretical underpinnings of CGE models permit more robust ‘out of sample’ modelling, particularly concerning structural shifts in the economy, albeit not easily resolved endogenously without assistance from other models (Nikas et al. 2018).

CGE models can either be static or dynamic. Most CGE models are static in nature where demand is derived for a one period utility function (Diao et al. 2012). Static models compare equilibrium before and after a shock or policy reform and represent the path of an economy from a benchmark equilibrium to a new equilibrium after a shock has impacted the economy (Kompas et al. 2018). While static models can provide a detailed representation of an economy within a particular time-period, they are unable to consider second-period effects that further change the trajectory of an economy after a shock has occurred. Dynamic models allow for changes in output growth due to policy reform that can be tracked over time.

There are two approaches to dynamic CGE modelling, a recursive dynamic approach and an inter-temporal dynamic (or perfect foresight) approach (Doukas et al. 2019). A recursive dynamic model consists of multiple static models linked to each other sequentially. In this approach selected parameters are updated based on modelling of inter-temporal behaviour and results from previous iterations. The assumption of this approach is that the current economic conditions are dependent on past outcomes but are unaffected by forward-looking expectations (Lefevre 2016). The representative agents in these models choose consumption or production during a given period that maximizes the discounted stream of their utilities or profits. Inter-temporal dynamic CGE models are based on optimal growth theory, where the behaviour of representative agents is characterized by perfect foresight.

Several CGE models have been developed to evaluate climate mitigation and adaption scenarios for South Africa. GTAP-E-PowerS is an adaptation of the GTAP-E-Power static CGE model (Nong 2020). This model includes a detailed power sector module and transmission and distribution. The UPGEM model includes a nested electricity production sector with eight competing generation technologies making it a soft-linked hybrid CGE model (van Heerden et al. 2016). IMACLIM-ZAF is an extension of the IMACLIM dynamic CGE model for South Africa. SAGE is a South African CGE model developed by the International Food Policy Research Institute (IFPRI).his model has been hard-linked to the SATIM energy systems model to create the bottom-up, top-down hybrid model SATIMGE which will be discussed in more detail in the next section.

3.6 Macro-econometric models

Like CGE models, macro-econometric models can be quite detailed in terms of sector representation and geography and are often used to evaluate climate policy. However, unlike CGE models, macro-econometric models do not assume market clearing in the short and medium run (Nikas et al. 2018). Instead, they are built around empirical observations of historical data which describe several interlinking energy–emissions–economic relationships (Lefevre 2016). These models simulate the dynamics of the real world by empirically estimating these economic relationships and have more freedom to model phenomena that are often inconsistent with some of the assumptions of optimization models (Scrieciu et al. 2013). Macro-econometric models allow for structural unemployment resulting from inadequate labour demand in the long run. The parallel development of macro-econometric and CGE models has led to ongoing debates and conflicting positions between the two approaches. One of the most widely cited climate macro-economic models is the E3MG global model and its extension the E3ME model for Europe (Scrieciu et al. 2013).

The E3ME model stands out for its unique capability to illustrate negative costs, indicating that the implementation of climate policies can result in upticks in employment and output. According to this model, shifting towards a low-carbon economy has the potential to bolster demand for labour and spur economic expansion. In contrast, numerous CGE models operate under the assumption that the economy perpetually operates at an optimal level, thereby viewing climate policies as supplementary costs (Nikas et al. 2018).

In general, macro-econometric models incorporate market imperfections and consider the potential benefits of climate policies in reducing these imperfections, such as barriers to adopting new technologies. The concept, known as ‘double dividends’, suggests that climate policies can address multiple market imperfections and have positive economic impacts beyond climate protection alone. However, they are not easily able to handle well ‘out of sample’ situations, which can occur in the long run.

South Africa is known to have a comprehensive social accounting matrix (SAM), and CGE models are the most popular models used for climate mitigation risk assessments in the country. The INFORM model is a macroeconomic simulation model used in South Africa which accounts for changes resulting from climate mitigation options (DAE 2014).

Table 2 presents a list of energy-economic models that have been used in South Africa, as well as how they can be categorized in line with various model classifications described above.

Table 1: Categorization of South African energy systems and energy-economic models

Model perspective	System coverage	Mathematical structure	South African models
Bottom-up	Partial equilibrium	Optimization	SATIM[2]; OSeMOSYS[3]; PypSA[4], PLEXOS[5]
Bottom-up	Partial equilibrium	Simulation	LEAP[6]
Top-down	Optimal growth IAM	Optimization	
Top-down/ Hybrid	Static CGE	Optimization	GTAP-E-PowerS[7]
Top-down/ Hybrid	Dynamic CGE	Optimization	SAGE[8], UPGEM[9], IMACLIM-SA[10], KLEM-ZAF[11]
Top-down/ Hybrid	Macro econometric	Simulation	INFORUM[12]

Source: authors' elaboration based on Anvari et al. (2022) and Lefevre (2016).

4 SATIMGE review

As mentioned above, SATIM is a bottom-up least cost energy systems optimization model which finds the least-cost energy pathways to meet future demand given various technical, environmental, and social constraints. SATIM is able to analyse the

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[2] SATIM is a full energy sector model with exogenous economic indicators and endogenous energy demand (Hughes et al. 2020). This model is held by the Energy Systems Research Group at UCT.

[3] The open-source energy modelling system (OSeMOSYS) is a simplified full energy sector model developed by Howells et al. (2011) and incorporated in the South African energy modelling system by the Department of Energy (DOE 2013). The DBSA has appointed a team led by the PwC to develop an updated South African power systems model using OSeMOSYS.

[4] The Python for Power Systems Analysis (PyPSA) model is an open-source energy systems model developed by Hörsch and Calitz (2017) and used in South Africa by the Council for Scientific and Industrial Research (CSIR) and Meridian Economics.

[5] PLEXOS is a power system optimization model used in the South African Integrated Resource Plan (DMRE 2019). The institutions using PLEXOS in South Africa include the CSIR, Eskom, Department of Mineral Resources and Energy (DMRE), National Business Initiative (NBI), and Boston Consulting Group (BCG).

[6] The long-range energy alternative planning tool (LEAP) has been applied to the development of the national energy efficiency strategy by the Department of Minerals and Energy (DME 2005). A LEAP model of the energy demand of the South African residential sector is held by the ESRG.

[7] An extension of the GTAP-E-Power model developed by Nong (2020) at the Institute for Food and Resource Economics at the University of Bonn, Germany

[8] The South African General Equilibrium (SAGE) model was developed by Diao et al. (2012) and is maintained by the International Food Policy Research Institute (IFPRI)

[9] A modified version of the UPGEM dynamic CGE model with a nested electricity production sector was used to model the economic impact of carbon tax in South Africa. It was developed byvan Heerden et al. (2016) at the University of Pretoria.

[10] IMACLIM-SA is a hybrid energy-economy model developed by Schers et al. (2015) at Centre International de Recherche sur l'Environnement et le Développement (CIRED).

[11] KLEM-ZAF is an extension of the compact 2-sector KLEM general equilibrium model developed at CIRED. See Soummane et al. (2019)

[12] The INFORUM macro-economic model was used to evaluate GHG mitigation by the Department of Environmental Affairs (DAE 2014)

effect of energy policies on electricity price and emissions but is not able to quantify the economy-wide implications of these policies. In order to analyse the full effect of particular energy pathways on the South African economy, households and other economic sectors of the eSAGE economy-wide model are linked to the SATIM energy model. eSAGE is an energy-extended version of the South African CGE model SAGE which disaggregates specific energy sectors to allow for better integration with SATIM. eSAGE is a recursive CGE, country-level, economy-wide model that simulates the functioning of the South African economy (Merven et al. 2017). In this section, SATIMGE is reviewed with respect to its potential usefulness and limitations for estimating finance needs to secure not only energy, but also water and food into a future with stronger climate change impacts.

4.1 SATIM

SATIM (South Africa TIMES model) is a model representation of South Africa's energy sector with significant detail on key energy sub-sectors (electricity, solid, liquid, and gaseous fuels, industry, residential, commercial, transport, and agriculture on the demand side). It is set up to allow specialists to analyse different least-cost energy sector futures, with freedom to update the model as the energy sector evolves. Users can change assumptions on, for instance, technology/fuel/commodity costs and availability, emissions, or other resource constraints, trade policies, and/or different economic and population growth estimates. SATIM also allows users to see how the energy sector could change over time under given assumptions. This is particularly useful for long-term modelling, where not only the end point is important, but the path to get to that end point is also of value. SATIM can respond to cost and constraint assumptions endogenously with investment and operations around technology options available in the model. Changes in technologies adopted impact both Industrial Processes and Product Use (IPPU) GHG emissions. Policy and technology options in the waste and agriculture, forestry, and other land use (AFOLU) sectors must also be specified exogenously.

SATIM is characterized by several key strengths. One notable aspect is its comprehensive representation of the energy system, which allows for the explicit accounting of emissions, including fugitive emissions, and fuel use across all significant sectors. This holistic approach facilitates the examination of trade-offs between sectors when mitigation measures are required and enables policy makers to target specific sectors for interventions. By representing the demand for energy services in all sectors, SATIM creates a platform for competition between demand-side changes (such as efficiency improvements, process modifications, and fuel switching) and supply-side alterations, providing an optimized energy pathway for South Africa to meet future energy service needs under policy or other constraints. For instance, the model allows for the exploration of scenarios where electricity generation increases its use of renewable energy (RE), or where demand sectors switch fuels (e.g. adoption of EVs or electric boilers) or adopt more efficient technologies, all aimed at reducing emissions (Hughes et al. 2020).

Another notable strength of SATIM lies in its high level of sectoral detail, which matches and improves on the energy balances published by the Department of Energy of South Africa. This attention to detail ensures the accuracy of base year demand. While base year updates may be irregular due to delays in publishing energy balances and national statistics, SATIM's detailed representation of demand at the energy service level, coupled with its flexibility in decoupling model years from data years, facilitates regular updates and maintains accuracy. Additionally, the model accounts for income changes over time, which play a significant role in determining the demand for transport and energy services in the residential sector. By accurately reflecting household income growth and electrification in the energy system, SATIM ensures consistency with economic growth. The model achieves this by linking its underlying drivers to the outputs of a CGE model, ensuring economically consistent scenarios and capturing the interplay between income growth, energy service demands, and sectoral development.

The electricity subsector of SATIM is temporally disaggregated, to capture daily and seasonal demand and renewable energy supply fluctuations. A high-resolution version of SATIM has recently been developed, modelling at 8,760 hourly time-slices per year.

The current SATIM model does not differentiate spatial diversity in supply and demand. It can also not capture heterogeneity in preferences and endogenous modal shifts in the transport sector. Addressing these limitations would require improved disaggregation, soft linking with choice models, and capturing city-specific characteristics.

4.2 SAGE

The CGE model of South Africa (SAGE) is a dynamic recursive, country-level, economy-wide model that simulates the functioning of the South African economy. This model is an extension of the core static CGE model used by the International Food Policy Research Institute (IFPRI) described in Lofgren et al. (2002). The behaviour of the economic agents of this model is based on adaptive expectations, rather than on the forward-looking expectations that underlie alternative inter-temporal optimization models (Thurlow 2004). SAGE provides a detailed and comprehensive representation of the South African economy including up to 104 sectors and commodities, five factors of production (capital and four labour groups) and 12 household categories (Anvari et al. 2022).

Within each period SAGE is solved subject to given levels of population, productivity, and capital supply. Between periods SAGE is updated to reflect population growth, technical change, and capital accumulation. New capital formation is determined endogenously based on previous-period investment levels and the relative profit of the different sectors. Once invented, capital becomes sector specific (Merven et al. 2017).

4.3 SATIMGE

The energy-extended version of SAGE has been hard linked to the full energy sector South African TIMES (SATIM) model[13]. Combining the two models captures the details required from the energy systems modelling with economic analysis to assess the impact of energy system changes on various sectors, markets, and agents in the economy (Merven et al. 2017).

[13] See Merven et al. (2017) for a detailed description of the linking process.

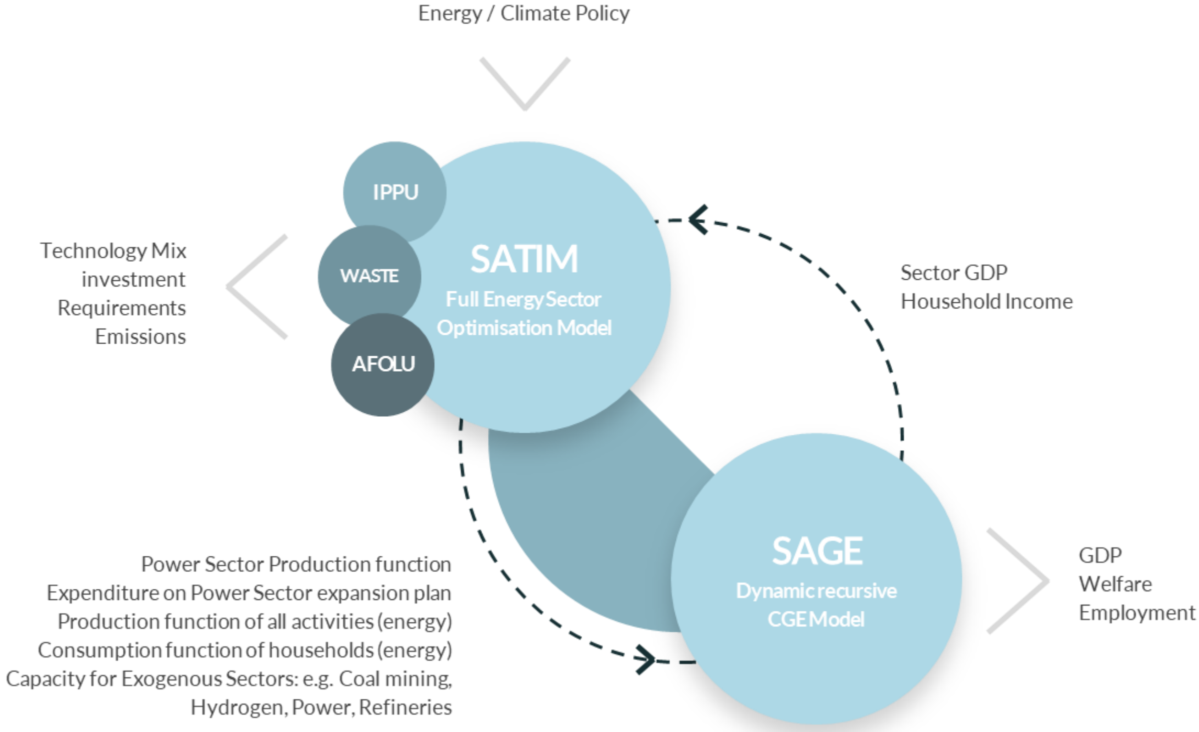
By developing and maintaining the models independently, experts in energy engineering and economics can focus on their respective domains and develop, test, and maintain the models separately. There have been several improvements made to the SATIMGE model since its conception, and the SATIMGE modelling framework has been used to evaluate climate mitigation pathways in several key studies (Hartley et al. 2019; Merven et al. 2017, 2021; Merven, Hartley, and Ahjum 2019; Merven, Hartley, and Schers 2020; Merven, Hartley, Mccall et al. 2019; Merven, Hartley, Schers et al. 2020; RSA 2022).

The models are run iteratively allowing information to be exchanged in both directions. In previous versions of SATIMGE, there were only connections between the power sector and eSAGE (Merven et al. n.d.). In this improved approach, connection points are established across all major energy-consuming sectors of the economy.

SATIM computes the least-cost energy technology mix based on assumptions about technology and fuel costs, as well as constraints such as demand and emissions. The resulting technology mix is then passed to eSAGE, which incorporates the new energy supply and demand composition. Aggregate investment in eSAGE is determined by assuming a macro adjustment process, where changes in aggregate final demand are shared proportionally across consumption, investment, and government spending. Investment in the exogenous sectors is allocated first, followed by competition for remaining funds among other sectors. eSAGE provides new projections of economic indicators, which are then fed back to SATIM to update demand and for further optimization. This iterative process continues until the models align in terms of energy utilization, CO2 emissions, demand, price, and technology mix.

The connection points between the models include the exchange of gross value added (GVA) at the sector level and household income per income group. The production function is adjusted differently across sectors, with energy intermediate inputs, capital, and labour inputs modified in the power sector, while other sectors only adjust energy intermediate inputs based on SATIM results. Household energy-related consumption and energy capacity expansion are also adjusted based on SATIM outputs. The annual expenditure on capacity expansion for exogenous sectors is aligned with SATIM outputs.

Figure 2: Iterative approach used in SATIMGE



Source: authors' adaptation of figure in Merven et al. (n.d.), with permission.

Further development of SATIMGE

SATIMGE is one of the most developed energy-economy models in the developing world. However, no model is perfect and there are various improvements that can be made to develop the model further and improve its ability to accurately determine the optimal mitigation and adaptation investment strategies that fall within the planned decarbonization pathways for South Africa.

One aspect that needs further development in the model is a better representation of other material flows in the CGE. Currently, the energy sector is the only sector in the model which has a good representation and tracking of physical units.

CGE models in general assume that the economy is on an optimal path which can achieve equilibrium via price adjustments and market clearing. This translates into an insignificant role for fiscal, monetary, and other macroeconomic policies to push the economy towards more sustainable outcomes (Scrieciu et al. 2013). Therefore, CGE models have no cyclical and financial sector dynamics. Financial dynamics need to be improved across all models and sufficiently included in financial stress testing.

Currently, the model can analyse climate scenarios at a national level and has not been spatially disaggregated to evaluate the optimal investment pathways and the associated macro- and socio-economic impacts of these at a provincial or local level. The SATIMGE model assumes that labour is mobile between sectors and geographies. This may not reflect the realities of the South African labour market in the short run. Aggregating nationally can also hide the extent of the impact mitigation and adaption policies as well as the physical risk of climate change at a local level. Adding spatial disaggregation to the model would allow for a more accurate representation of the impact of mitigation pathways and climate risk in various regions across South Africa. Spatializing the energy systems model will also allow for a better representation of the cost of renewable energy investment.

The SATIMGE model does not incorporate a climate damage function, and therefore the model does not account for the physical risk of climate change. Accounting for these climate vulnerabilities is important to more accurately evaluate different mitigation investment pathways that extend beyond the energy sector and incorporate the inter-relationships and trade-offs in the food-energy-water nexus. Links could be created between SATIMGE and another CGE-based climate risk model for South Africa, the Systematic Analysis for Climate Resilient Development (SACRED) framework, which will be discussed in Section 6 of this paper.

5 Macro-financial modelling

5.1 South Africa fiscal environment

South Africa experienced significant improvements in public deficits and its public debt/GDP ratio during the 2002–08 period and entered the 2008 financial crisis with a strong fiscal position, with net debt-to-GDP levels at approximately 30% (Makrelov et al. 2020; Yilmaz and Godin 2020). Due to this strong position, the South African government was able to implement counter-cyclical increases in government spending during the global recession in 2008 and 2009. However, after several supply-side shocks, the fiscal expansion pursued by the South African government was no longer sustainable and government debt balances increased significantly (Makrelov et al. 2020). South Africa's debt-to-GDP ratio increased from 35.1% in 2010 to an estimated 73.9% in 2023 (National Treasury 2024). It has been argued that the South African government is now facing a debt trap (Burger and Calitz 2020).

For South Africa to reach its nationally determined contribution (NDC) of 350–420 $MtCO_{2e}$ by 2030, there will need to be significant public and private investment in climate mitigation and adaption (RSA 2022). The Just Energy Transition Investment Plan (JET IP) of South Africa estimates that the financial investment required to proceed towards a low-carbon and climate-resilient economy over the next five years will cost ZAR1.5 trillion (US$98.7 billion). Some of the analysis supporting these estimates was done using the SATIMGE framework. The International Partner Group[14] (IPG) has committed to mobilizing an initial amount of US$8.5 billion, approximately 9% of the required finance (RSA 2022). The remainder of the required investment is expected to come from a mixture of public and private finance. With the South African public debt ratio and debt servicing costs rising, this raises the question, will the South African economy be able to carry the corresponding additional private debt burden?

[14] A partnership between South Africa and the governments of France, Germany, United Kingdom, United States, and the European Union.

5.2 The role of the financial sector in the low-carbon transition

As mentioned above, the South African low-carbon transition requires significant investment in energy research and development, infrastructure, and supply chains that could substantially exceed what might have been invested in this sector in an otherwise business-as-usual scenario (Mercure et al. 2019). The question of how this investment will be financed and whether more investment resources can be mobilized are key to understanding the economics behind this low-carbon transition (Pollitt and Mercure 2018). The central bank and financial sector have a critical role to play in South Africa's transition to a low-carbon and climate-resilient economy. A favourable environment for private sector investors is crucial. The transition away from fossil fuel industries is also likely to have strong financial implications on South Africa's economy. There is a need for increased awareness of climate-related risks in the financial sector. It has been argued, in the global context, that a too rapid movement to a low-carbon economy that does not fully account for the associated financial risks could materially damage the financial stability of an economy (Bovari et al. 2018).

There are two main avenues through which climate-related risk may impact the financial sector. Firstly, there is the risk of physical damage due to climate change. Extreme weather events can have a large impact on the assets of households and businesses as well as their balance sheets. Secondly, there is the transition risk, or the risk of the economic disruptions caused by the transition towards a low-carbon economy. This is reflected in the risk of stranded assets due to the pressure of global commitments resulting in the early retirement of coal mines and coal-fired power stations or impacting other fossil fuel industries (Campiglio et al. 2017). If fossil fuel companies were to write off these assets, investors in these companies would experience a large drop in the value of their assets. Stranding of assets will lead to a sharp decrease in the value of the companies that own them as well as the market price of the financial assets they have. This could have cascading effects through the financial sector and economy. South Africa exports also potentially face punitive border tax adjustments on certain commodities and markets as outlined in a Trade & Policy Strategies (TIPS) policy brief (Monaisa 2023).

There is increased interest by central banks in the financial risk associated with the low-carbon transition and how to effectively stress test their financial system for climate-related matters (Campiglio et al. 2017). As mentioned above, the majority of climate- and energy-economy models evaluating the impact of physical and transition risk in South Africa are equilibrium models which in general overlook the role of financial intermediaries. A paper by the South African Reserve Bank (SARB) highlighted the need for the integration of different modelling tools to develop scenarios for climate-related stress testing to assess the impact of climate change, translate these impacts into macroeconomic scenarios, and evaluate the subsequent financial sector outcomes in South Africa (Anvari et al. 2022).

5.3 Stock-flow consistent models

The importance of monetary policy has received renewed attention due to the slow recovery that many countries faced in the wake of the 2008 financial crash. With this renewed interest in monetary policy came an increase in the use of stock-flow consistent macroeconomic models (Nikiforos and Zezza 2017). Stock-flow consistent models are typically non-neoclassical and describe the economy in terms of stocks (wealth, debt, capital) and flows (income, spending, investment). The major benefit of using stock-flow consistent modelling is that it creates linkages between the real and financial sides of the economy and treats them in an integrated way. These linkages provide a natural way to examine issues relating to the financial vulnerability of an economy and how this links to real outcomes (Nikiforos and Zezza 2017). Stock-flow consistency implies that changes to the balance sheets of one institution must be matched by changes in the balance sheets of other institutions. A major difference between stock-flow consistent models and other economic models is that the cyclical flow changes affect the long-term real and financial behaviour of institutions through their impact on the respective institutions' assets and liabilities stock (Makrelov et al. 2020).The building of stock-flow consistent models requires a lot of attention to accounting consistency, as well as detailed modelling of the real and financial sides of the economy and their interdependencies (Nikiforos and Zezza 2017). This calls for careful modelling of inter-relationships among balance sheets and economic agents (Yilmaz and Godin 2020). Building a stock-flow consistent model is data intensive and many of these models face data limitations which do not allow for the sectoral information that is typically required for policy analysis. However, stock-flow consistent models have been used to address some important high-level questions related to the environment and financial stability (Pollitt and Mercure 2018).

There is a growing body of literature which uses stock-flow consistent models to evaluate the impact of a low-carbon transition in developing economies. Bovari et al. (2018) developed a stock-flow consistent macroeconomic model that combines the economic impact of climate change with the pivotal role of private debt. There is growing evidence of strong links between monetary policy in global financial centres and small open economies like Colombia and South Africa (Yilmaz and Godin 2020). GEMME is a stock-flow consistent prototype growth model which has been established for various developing countries including Columbia (Yilmaz and Godin 2020). This model was developed to replicate the empirical regularities in developing economies following policy rates and capital inflows. EIRIN is a calibrated stock-flow macro-financial country-level modelling framework used by the World Bank which identifies risk transmission channels and financial outputs such as sectoral non-performing loans and probabilities of default (World Bank 2022). All three of the stock-flow consistent models mentioned above incorporate a damage function through modelling the risk of capital stock destruction and spillover effects.

A stock-flow consistent general equilibrium model for South Africa was developed by Makrelov et al. (2020)to analyse the implications of financial sector dynamics for fiscal expenditure in recessionary conditions. This stock-flow consistent model was used to assess the impact of fiscal expenditure in the immediate period after the 2008 crisis in South Africa. Makrelov et al. (2020) noted the availability and quality of information as a major constraint in developing their model. The flow of funds data available for South Africa provides for 11 institutional units and 23 financial instruments. These are aggregated into six institutions and five financial instruments; this aggregation is driven by other data limitations. A major limitation facing macro-financial modelling globally is data gaps. In South Africa there is a lack of credit data by economic activity classification or municipal level, which has hindered the development of granular models with credit and economic linkages (Anvari et al. 2022).

5.4 Financial dynamics of climate-economy models

A key issue that needs further advancements is how to treat the representation of investment, money, and finance in climate-economy models in assessing the real impacts of a low-carbon transition. This problem reflects in most IAMs underestimating the role of finance on the real economy, including stranded assets, or the physical risk of climate change to assets (Mercure et al. 2019). The models that are used to assess the macroeconomic impacts of climate and energy policy fall broadly into two groups. These are CGE models and macro-econometric models (Pollitt and Mercure 2018). There has been debate in the literature around the theoretical underpinning of these two groups of models and which modelling framework is best suited to estimate these impacts. In practice, CGE models make up the majority of the climate-economy IAMs internationally (Scrieciu et al. 2013).

A criticism of CGE models is that they do not have a realistic representation of cyclical and financial sector dynamics (Scrieciu et al. 2013). However, this criticism is aimed particularly at more static CGE models with neoclassical closures. There have been significant advancements to CGE modelling techniques which incorporate dynamic components allowing for the representation of stock. Recursive dynamic CGE models like SATIMGE implement closures that deviate from neoclassical assumptions of full employment. However, the representation of debt and finance within these models is an issue which has yet to be resolved. Some progress has been made in the representation of financial dynamics in South African CGE modelling through stock-flow consistent models such as the one developed by Makrelov et al. (2020).

Pollitt and Mercure (2018) found that CGE models that are used for climate and energy policy typically make assumptions about the financial system that do not match up with reality. In typical CGE models, increases in investment due to mitigation policy are funded either from a reduction in investment in other sectors or an increase in savings at the expense of current consumption. These assumptions often lead to the 'crowding-out'[15] of investment and negative economic impacts for climate policies.

In contrast, it has been argued that macro-econometric models, which follow non-equilibrium economic theory and adopt a more empirical approach, apply a treatment of the financial system that is more consistent with reality (Mercure et al. 2019; Pollitt and Mercure 2018). These models allow for banks to increase lending if investment opportunities are sufficiently attractive. This leads to an increase in net credit and the broad money supply, in turn stimulating real economic activity and leading to higher rates of output and employment. Although these models also have major flaws, they show that green investment need not 'crowd-out' investment in other parts of the economy and therefore may offer economic stimulus (Pollitt and Mercure 2018).

While the treatment of the financial sector could be considered more realistic in non-equilibrium macro-econometric models compared to general equilibrium models, both modelling techniques in general do not feature detailed financial markets and do not

[15] 'Crowding-out' can be broadly defined as the phenomenon where an agent (such as the government, businesses, or individuals) borrows substantial funds for productive capital investment. Under specific conditions, this borrowing may redirect funds that would have otherwise been utilized elsewhere in the economy, causing an increase in the price of finance (interest rates) and, consequently, making it more challenging for alternative projects to secure funding. The concept of crowding-out can extend to physical capital or labour, affecting the equilibrium prices or wages in their respective markets (Mercure et al. 2019).

sufficiently consider financial barriers and opportunities in the transition to a low-carbon economy(Sanders et al. 2022). For example, neither CGE nor macro-econometric models in their current form are well equipped to assess the financial and macroeconomic impacts of bankruptcies in large firms, the public and private debt burden, or stranded assets (Pollitt and Mercure 2018). There is a lot of uncertainty around the 'carbon bubble'[16] and the impact of transition risk on the financial sector. Understanding the extent to which transition risk interconnects with the financial system and how stranded assets can potentially trigger not only financial crisis but also have real economic consequences is key to designing mitigation policies. The financial dynamics of climate-economic models need to be improved and sufficiently included in financial stress testing. There is clear merit in further developing stock-flow consistent models which are better suited to evaluate the impact of debt and transition risk (Pollitt and Mercure 2018).

Improvements could be made to SATIMGE in its handling of debt and finance through linkages to the stock-flow consistent CGE model developed by Makrelov et al. (2020). The development of a South African version of the stock-flow consistent macro-financial GEMME model is also currently underway. This will break from the standard approach of optimization and equilibrium modelling used to evaluate climate policy and the energy transition in South Africa and bring a new perspective to the financial risks associated with climate change and the South African low-carbon transition.

6 Damage function modelling

Climate change is the most significant global externality, threatening security, livelihoods, and the economy. It has a major impact on the productivity of different economic sectors as well as labour groups (Shayegh et al. 2021). In order to properly analyse the impact of policy and investment, it is essential that models include some representation of the physical risk associated with climate change. Incorporating this physical risk and vulnerability to it can inform investment decisions on adaption (Nordhaus 2019; Stern et al. 2022). Many climate-economy models include damage functions which attempt to translate the risk associated with changing weather patterns into quantifiable economic damages. The damage function expresses physical and environmental outcomes as a function of climate variables.

6.1 South African climate change impact assessment models

There is a growing body of literature that attempts to assess the impact of different climate change scenarios on economic productivity in South Africa using integrated assessment frameworks (Cammarano et al. 2020; Cullis et al. 2015; Ding et al. 2021; Hartley et al. 2021; Ogundeji et al. 2018; Shayegh et al. 2021). A study by Cammarano et al. (2020) investigated the impact of climate change on crop productivity and income of commercial maize farms in north-east South Africa. The Agricultural Model

[16] The 'carbon bubble' has been described as 'a situation where asset prices (of fossil fuel reserves) appear to be based on implausible or inconsistent views about the future' (Stenek 2014). This refers to the market value of fossil fuel reserves which reflect the perception that they are going to continue to be exploited, which contradicts the imperative of limiting greenhouse gas emissions. The unburnable fossil fuel reserves are referred to as stranded assets (Stenek 2014).

Intercomparison and Improvement Project Regional Impact Assessment (AgMIP-RIA) tool was used. Their analysis found that maize production in the north-eastern region of the Free State province will decrease between 10% and 16% due to climate change. This will lead to a decrease in agricultural output and an increase in poverty. Shayegh et al. (2021) used an analytical model of overlapping generations to study the impact of rising temperatures on economic productivity and labour availability in rural areas in South Africa. They found that climate change is likely to lead to a decrease in labour supply and welfare in terms of output per adult. Ogundeji et al. (2018) developed the Ceres Dynamic Integrated Model to simulate the impact of climate change on water availability and evaluate the potential effect of adaptation strategies. This study shows the importance of adaptation strategies in protecting the livelihoods of farmers from the negative impacts of climate change. A city-level human natural system model was developed for Cape Town which consisted of an agent-based model and a regional hydrologic model (Ding et al. 2021). This model was then used to study the connection between the agricultural, urban, and hydroelectric generation sectors.

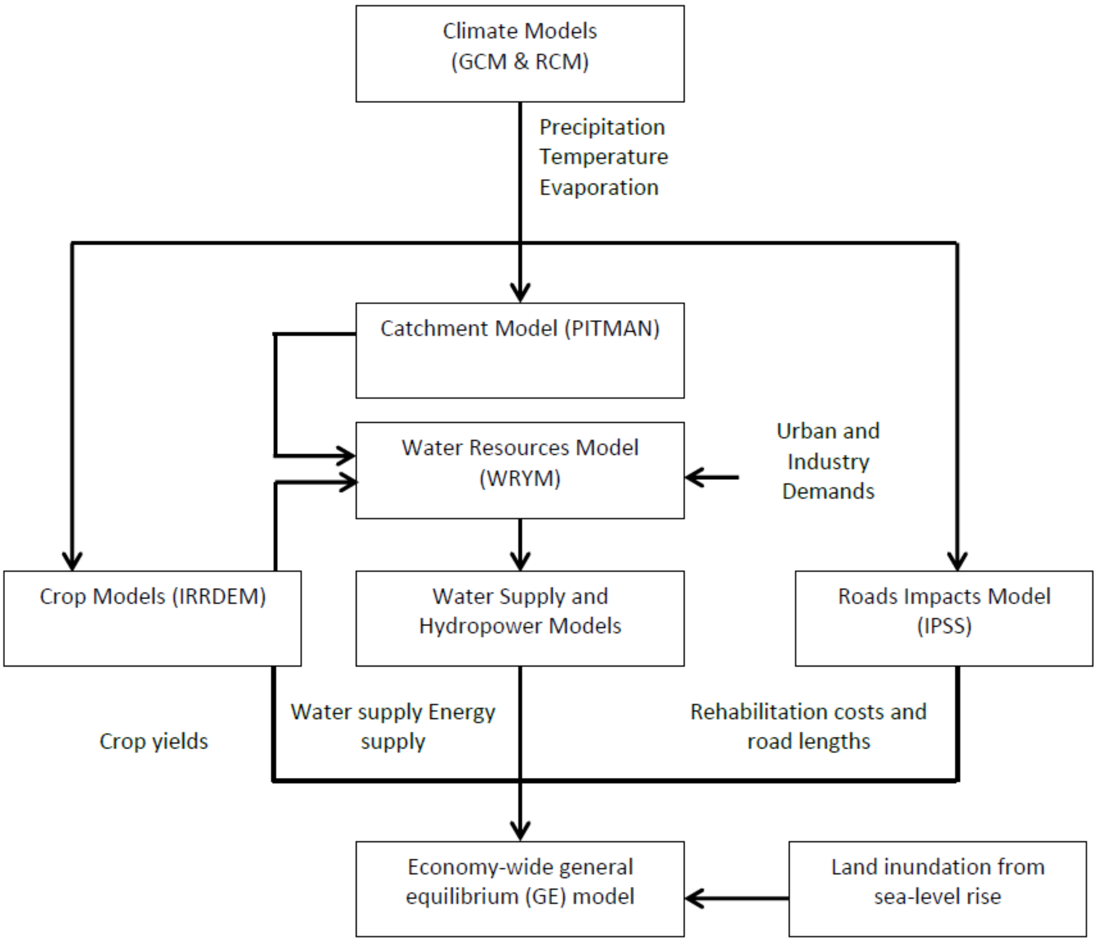
6.2 SACRED framework

Cullis et al. (2015) were the first study to attempt to assess the potential impact of climate change on the South African economy using an integrated approach. This study highlights the importance of spatial and temporal detail as they found significant variation in climate impacts between regions. This study utilized the International Food Policy Research Institute's (IFPRI) System Assessment of Climate Change Resilient Development (SACRED) framework which had been previously applied to assess the impact of climate change in other regions in Southern Africa (Arndt et al. 2011; Schlosser and Strzepek 2015). SACRED is an integrated framework which combines the use of i) climate models, ii) country specific biosphere models, and iii) economic models. SACRED incorporates different bottom-up impact assessment models into the South African CGE model (SAGE). Cullis et al. (2015) evaluate three channels through which climate change impacts the economy: road infrastructure, water supply, and crop yields. Figure 33 represents these channels evaluated in the South African SACRED framework.

The SACRED framework links its climate model to climate scenarios from the Integrated Global System Model (IGSM). To get the regional patterns of impact, this IGSM is combined with regional data taken from general circulation models of the earth atmosphere from the climate model intercomparison project (Hartley et al. 2021). Multiple climate future scenarios are modelled in order to present decision makers with an estimate of the likely risk range of climate change impacts.

The climate models generate output on the future precipitation, temperature, and evaporation in specific regions. These outputs are then used as inputs into the rainfall run-off and water resource model for South Africa, a crop model, and a road infrastructure model adapted for South Africa. The outputs from these models combined with an assessment of the additional economic impact of climate change are incorporated into a version of SAGE which has subnational detail in the water and agriculture sectors (Cullis et al. 2015).

Figure 3: SACRED framework



Source: Figure 1 Cullis et al. (2015: 8), reproduced with permission.

Including a climate damage function enhances the accuracy of climate-economy models by incorporating climate risk to various sectors and regions. Including these functions can help to evaluate the distributional impacts of climate change on socio-economic and macroeconomic outcomes. This is specifically important in the WEF nexus due to the impact that climate change will have on water availability and temperatures, which has deep links to food production. Extreme weather events often have significant impacts on infrastructure which can severely undermine water, energy, and food supply in regions that are affected. The regional variability of climate impacts and the often-extreme effect of localized natural disasters makes it difficult to include damage functions on nationally aggregated models. Spatial resolution is particularly important to accurately incorporate the impact of climate damage in climate-economic models.

7 Regional impacts and climate-economy models

The lack of spatial resolution of models has consistently been raised as a major limitation of many climate-economic models (Anvari et al. 2022; World Bank 2022). When evaluating the cost of mitigation as well as vulnerabilities to transition and physical climate risk, nationally aggregated models often hide the severity of regional impacts.

Decarbonizing the South African electricity sector will require an accelerated transition away from coal-fired generation. The nature of coal-fired generation has resulted in most of the generation capacity in South Africa being centralized in Mpumalanga, and to a lesser extent Limpopo, Free State, and Gauteng. Renewables on the other hand can be distributed widely across all provinces. Distributed electricity generation from renewable sources is preferred as it can help diversify the power system and reduce long-distance transmission losses. In the long term this will give rise to many regional sustainable development opportunities and create more employment opportunities than currently exist in the electricity sector (Hartley et al. 2019; RSA 2022).The transition toward renewable generation could potentially lead to significant changes in regional economies all around South Africa. In order for the transition of the South African energy sector to be just, it is essential that new economic opportunities are created in areas that will be worst affected by the shift away from coal.

Disaster or policy action (e.g. mine closure) often has a concentrated impact in smaller regions. The local impacts are difficult to detect in nationally aggregated models. In models with representative households, the saving and borrowing constraints of the household representative agents of these models are immediately affected by disaster. There is also financial risk associated with early mine closure, not only for financial institutions and industry with shares in coal mines but for representative households in regions where large-scale mine closure is expected. Several studies have noted the housing price risk associated with mine closure in mining towns (Cloete and Marais 2021; Marais et al. 2022; Siyongwana and Shabalala 2019). There is also a risk associated with indebted municipalities in affected regions who are ill-equipped to deal with the risk associated with mine closure in the face of climate change (Siyongwana and Shabalala 2019). The severity of impacts of disasters and mitigation policies are underestimated by models when lumping those affected and unaffected households together, and thus the post-shock adjustment in models can be overestimated. The post-shock adjustment speed used in climate-economy models are also estimated from empirical data. However, shocks that impact a specific market and that require shifts in labour demand through skills and spatial distribution may lead to larger disruption than observed historical averages (World Bank 2022).

There are various advantages to increasing spatial resolution when modelling optimal energy investment for climate mitigation. Spatially disaggregated models allow for a more accurate representation of regional differences in energy resources, infrastructure, demand patterns, and economic factors. A study by Aryanpur et al. (2021) found that finer spatial resolution in energy systems models can offer significant value added into energy systems optimization when a country has regions with variable renewable energy potential. Spatially explicit models can help with infrastructure planning as they can analyse the optimal location and capacity of power plants, transmission lines, renewable energy instalments, and other energy-related infrastructure. In the South African energy transition, policies will need to be implemented at a national and regional scale. Energy-economic models with spatial detail can consider spatial factors, like resource availability, energy demand patterns, and socio-economic characteristics. This is crucial in policy analysis to allow policy makers to assess the distributional impacts of different policy options.

8 Conclusion and recommendations

Energy systems and economic models have been extensively used to evaluate the impact of climate mitigation policy on an economy. This review has shown that there exist several tools for modelling South Africa's energy systems and South Africa's economy. Also, several studies have been undertaken to understand the likely impacts of climate change on South Africa's economy.

Energy system models are of a partial equilibrium nature, treating the larger economy as exogenous to energy modelling; furthermore, most models are focused on the electricity system only. Both simulation and optimization models exist for South Africa. The economic models used in South Africa are mostly general equilibrium models.

There are a small number of hybrid models that have linked energy systems to economic modelling in South Africa. The most developed of these is SATIMGE, which has been used extensively to inform climate mitigation and economic policy. However, it currently does not capture climate-change-induced economic damages or detail on the financial dynamics of the economy; furthermore, whilst it is rich in sectoral detail, it captures no spatial detail. Investment needs to achieve the energy transition have been calculated with the aid of SATIMGE.

Due to the extensive investment needed, the financial sector, including the central bank, plays a crucial role in supporting the transition to a low-carbon economy. Climate-related risks can impact physical assets and cause economic disruptions through mitigation policies. As such there is increased interest in stress testing for climate vulnerability in the financial sector. Stock-flow consistent models, which integrate the real and financial aspects of the economy, can be used to assess the impacts of accelerated energy infrastructure investment needed to mitigate climate change and the associated role of private debt. However, there are data limitations and a need for better integration of financial dynamics in macroeconomic models to effectively analyse climate risks and conduct stress tests.

The SACRED model framework has been used to assess the impact of climate change on the South African economy in an integrated way. SACRED is an integrated framework which combines the use of climate models, regional biosphere models, and economic models. It incorporates different bottom-up impact assessment models into a version of the South African CGE model (SAGE) with subnational detail in the water and agricultural sector.

Climate-economic models with low levels of (or no) spatial disaggregation have been criticized for hiding regional impacts and hindering accurate cost assessment and vulnerability analysis. The transition away from coal in South Africa requires a shift towards decentralized renewable energy generation to diversify the power system, create employment, and foster regional sustainable development, while taking into account the current and future bottlenecks in the power grid. However, localized impacts, such as mine closures, pose financial risks to households, industries, and municipalities. Current models fail to adequately capture these concentrated effects. Increasing spatial resolution offers benefits by accurately representing regional disparities, aiding infrastructure planning, and enabling policy makers to assess distributional impacts of policies based on resource availability and socio-economic characteristics at finer scales.

If SA-TIED Phase II is to estimate investment needs and financial sector dynamics across the energy, water, and food production systems in the face of climate change, the following should be considered:

1. Water system and food system investment requirements are more of a climate adaptation challenge than climate mitigation; the SACRED framework is likely better suited to estimate these. Since SACRED, like SATIMGE, links to a version of SAGE, there should be consistency across the results.
2. If there is an interest in the financial dynamics that arise out of the very large investments required for the energy transition, for water and food sector adaptations, then a simulation-type macro-econometric model should be used. Such a macro-financial stock-flow consistent model, like that developed by Makrelov et al. (2020), should ideally draw on the same underlying datasets (e.g. the same SAM) as SAGE, so that there is consistency between the different models and linkages between the two models can be made.
3. The South African stock-flow consistent macro-financial GEMME model that is under development will bring a new perspective to the financial risks associated with climate change and the low-carbon transition. Insights from this model could be used to develop scenarios for climate-related stress testing to assess the impact of climate change and the low-carbon transition and evaluate the subsequent financial sector outcomes in South Africa.
4. For further refinements to its economic analysis, SATIMGE should incorporate a climate damage factor. This can be done through links to the SACRED framework which links physical climate vulnerability to economic outcomes for South Africa.
5. Climate damage improvements to SATIMGE, the decentralized nature of renewable energy, and associated justice considerations of the energy transition all require that a level of spatial disaggregation be added to the SATIMGE model. There will be significant value add by adding spatial resolution to the model for optimal energy investment planning. It is noted that such spatial disaggregation exists for the water (although very old now), food, and road transportation aspects captured in the SACRED framework. Spatial disaggregation in SATIMGE would require a significant investment in developing the required underlying datasets. As a first pass, this could be done at a provincial level, which would require the following:
    a. Updated provincial SAMs;
    b. Provincial energy balances;
    c. Development of provincial level simplified power grid models.

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