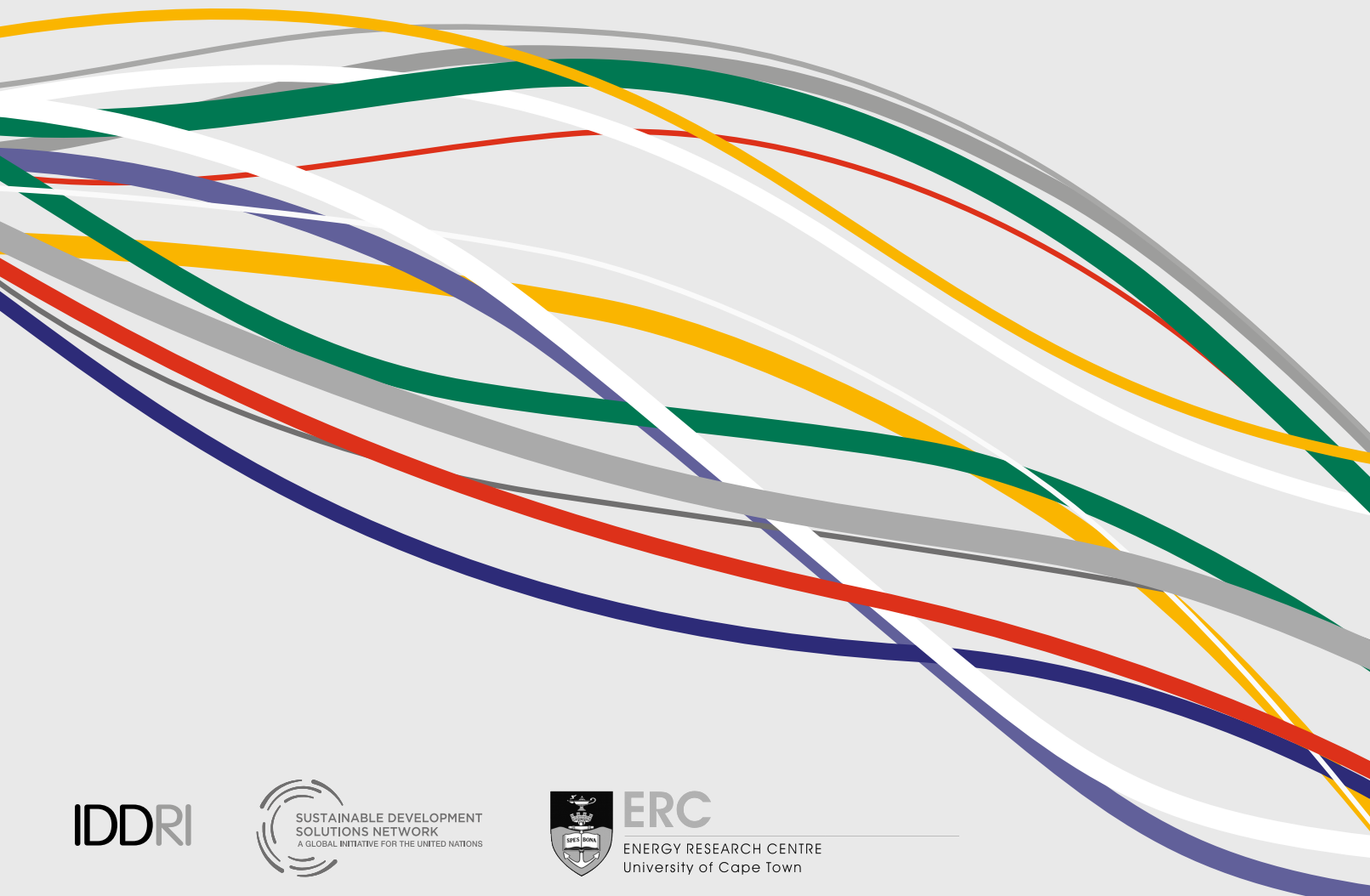


pathways to
deep decarbonization
in South Africa



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Deep Decarbonization Pathways Project

The Deep Decarbonization Pathways Project (DDPP), an initiative of the Sustainable Development Solutions Network (SDSN) and the Institute for Sustainable Development and International Relations (IDDRI), aims to demonstrate how countries can transform their energy systems by 2050 in order to achieve a low-carbon economy and significantly reduce the global risk of catastrophic climate change. Built upon a rigorous accounting of national circumstances, the DDPP defines transparent pathways supporting the decarbonization of energy systems while respecting the specifics of national political economy and the fulfillment of domestic development priorities. The project currently comprises 16 Country Research Teams, composed of leading research institutions from countries representing about 70% of global GHG emissions and at very different stages of development. These 16 countries are: Australia, Brazil, Canada, China, France, Germany, India, Indonesia, Italy, Japan, Mexico, Russia, South Africa, South Korea, the United Kingdom, and the United States.

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The Sustainable Development Solutions Network (SDSN) was commissioned by UN Secretary-General Ban Ki-moon to mobilize scientific and technical expertise from academia, civil society, and the private sector to support of practical problem solving for sustainable development at local, national, and global scales. The SDSN operates national and regional networks of knowledge institutions, solution-focused thematic groups, and is building SDSNedu, an online university for sustainable development.



The Energy Research Centre is a multi-disciplinary energy research centre, housed in the Faculty of Engineering and the Built Environment at the University of Cape Town. The Centre conducts high quality, targeted and relevant research as well as offering postgraduate opportunities at the Masters and PhD levels.

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ERC - Energy Research Centre

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Executive Summary

This report is part of the global Deep Decarbonization Pathways Project (DDPP), which aims to understand and demonstrate how countries can transition to a very low-carbon economy. The DDPP is a collaborative global initiative composed of leading researchers and research institutions from 16 countries that collectively are responsible for more than 70% of current global greenhouse gas (GHG) emissions.*

The South African country research team explored deep decarbonization pathways that focused on development and climate, putting equal emphasis on both goals. Satisfying multiple objectives, e.g., employment, income and GHG reductions, is critical as meeting a carbon constraint is one of many goals, and not necessarily the highest priority in a country such as South Africa, which has extreme and persistent poverty and high unemployment rates. Decarbonization pathways are connected to domestic economic and social structures, as well as global trade, prices, financial flows and international agreements.

This report presents the results of two illustrative deep decarbonization pathways for South Africa. Both scenarios are aimed at improving development metrics within a 14 Gt CO₂-eq cumulative energy sector carbon constraint. A linked modeling approach is utilized, building on long experience with energy models at ERC and adding a linkage to an economy-wide model. The first scenario explores ways to decrease unemployment by incentivizing growth in sectors with low-carbon emissions and high levels of labour absorption: this is the Economic Structure Scenario. The second scenario mimics significant improvements to the education and training sectors and injects high skilled labour into the economy fundamentally changing the labour force: it is known as the High Skills Scenario.

In both scenarios, GDP per capita increases by 170% from 2010 to 2050. The population in the low-income bracket, essentially a below-poverty-line category, decreases from 50% to ~18% in both scenarios by 2050, a marked improvement. The Economic Structure Scenario is more successful in reducing unemployment, but yet only halves the currently high official unemployment rate of 25% to 12%. While improving the educational system, as modeled by the High Skills Scenario, is probably essential in any future South Africa, unemployment is only reduced by a quarter, to 18%, even by mid-century. These results,

* The DDPP was co-founded and is led by the Sustainable Development Solutions Network (SDSN) and the Institute for Sustainable Development and International Relations (IDDRI).

as well as the bold assumptions made to achieve them, illustrate the intensity of the challenge of reducing poverty and emissions.

Identifying key sectors of the economy and creating an environment for growth in these sectors is likely to promote development and ease the transition to low-carbon growth for South Africa. However, education, inadequate training and unemployment present huge constraints to economic development in South Africa. We find that merely supplying higher skilled labour to the South African labour pool, without generating higher demand for goods in the economy or changing the current structure of the economy, is not sufficient to get South Africa to a more acceptable rate of unemployment, ~ 5%. Further research might focus on solutions that provide incentives for growth in sectors that are low-carbon and labour intensive; however, significant policy intervention and restructuring would be required, especially with regard to labour market challenges.

Though the two socio-economic scenarios met development metrics to differing degrees, both successfully met the 14 Gt energy system CO₂-eq constraint. In South Africa, decarbonization of the electricity sector is critical for meeting emissions constraints, as power supply currently accounts for just under half of national GHG emissions. Electricity sector GHG emissions decrease from 226 Mt CO₂-eq in 2010 to 11 Mt CO₂-eq in 2050 due to a complete phase out of coal-fired power generation as current and in-construction plants reach retirement, and due to the introduction of large amounts of solar (photo-voltaic -PV and concentrated solar power -CSP) and wind generation. As the electricity sector decarbonizes, other sectors switch to increased electricity use as well as continuously increasing energy efficiency of end-use technologies. In the Economic Structure Scenario, the agriculture sector sees significant growth, which results in the liquid fuel production sector having to decarbonize more rapidly to offset agriculture emissions. In contrast, the High Skills Scenario sees growth that largely maintains the current economic structure, and the liquid fuel sector decarbonizes less. In fact, the coal-to-liquids (CTL) sector is retained and the existing plants retire in 2040 as planned. This is one example of how domestic socio-economic policy choices impact options for decarbonization. This report presents modeled scenarios—whether it can be done in reality depends on economic, social and political factors, both domestically and internationally.

The current structure of the economy, rigidities in the labour market, and the current skills-profile of the workforce impede development in the absence of implausibly high GDP growth rates. This initial analysis suggests that the answer of how to achieve mitigation and development goals remains elusive, as unemployment rates remain unacceptably high in 2050 in both scenarios. Development and climate are both complex problems in themselves, and we offer no easy solutions for addressing them in tandem. However, this report does show that multiple objectives can be pursued, and that significant improvements are technically possible. More understanding based on in-depth and country-led research is needed to really meet the challenges of zero poverty and zero emissions.

pathways to **deep decarbonization** *in South Africa*

1 Background

The Deep Decarbonization Pathways Project (DDPP) was co-founded and is led by the Sustainable Development Solutions Network (SDSN) and the Institute for Sustainable Development and International Relations (ID-DRI). The DDPP is a collaborative global initiative composed of leading researchers and research institutions from the 16 countries that contribute more than 70% of global greenhouse gas (GHG) emissions: Australia, Brazil, Canada, China, France, Germany, India, Indonesia, Italy, Japan, Mexico, Russia, South Africa, South Korea, the United Kingdom and the United States. The goal of DDPP is to provide well-researched information on how individual countries can reduce GHG emissions to levels consistent with limiting the anthropogenic increase in global mean surface temperature to less than 2 degrees Celsius (°C), while meeting their national socio-economic development imperatives. The 2°C goal requires a reduction in global GHG emissions by the second half of the 21st century to a global net zero, with some countries simultaneously facing development-related challenges, e.g., poverty reduction and enhanced provision of energy services. At the 2050 time horizon adopted

in the DDPP analysis, this objective requires reaching significant decarbonization of energy systems, one measurement of which is a global average below 2 tons CO₂/capita. This transition is referred to as “deep decarbonization” and it will require global cooperation. While a global average below 2 tons CO₂/capita will be required, individual country teams set their own objectives for emissions pathways. The South African research team adopted a cumulative emissions budget to 2050 based on domestic government climate change policy. The South African government policy explicitly takes into account an assessment of what a fair South African contribution to reducing global emissions would be (DEA, 2011).

In the general DDPP back-casting approach towards the global objective, each country team prepares pathways based on national statistics, relevant research and expertise in conjunction with quantitative models, if available. These pathways are combined into a common framework known as the dashboard, which aggregates country-level data and results, in an attempt to ensure transparency of the transformations supporting the development-and-mitigation narratives. An important

aspect of the approach to this research has been the interaction of country teams with each other, as well as with the DDPP coordination and technical support team. The initial goals were loosely specified, which allowed the international teams to discuss and formulate how these would be interpreted at a country level, with international coordination achieved through group work and the dashboard. A core principle was the “bottom-up” approach: country teams would decide how their national priorities, conditions and research capacities would inform their research. For example, some teams do not use models and have limited national statistics. Therefore, they populate the DDPP created dashboard directly and use its calculator feature to calculate emissions trajectories. Other teams use existing sophisticated fully-linked economic and energy system models with complete sets of national statistics. The dashboard can then be analyzed to evaluate how deep decarbonization can be achieved, how it relates to crucial development priorities and to assess the potential consistency of the aggregate results with the 2°C goal. A key output will be assessing what this cooperation might require, as seen from a bottom-up country perspective.

1.1 Objectives of the Research and Report

The key objective of the South African DDPP analysis is to describe a set of pathways that are within credible and acceptable socio-economic development trajectories, as well as achieving deep decarbonization. In using the terms “credible and acceptable,” we acknowledge that, first, South Africa is an upper mid-

dle-income developing country and therefore cannot explore deep decarbonization of the energy system without recognizing the socio-economic conditions that it faces as a developing country. Second, that given the broad range of stakeholders in socio-economic development and emissions reductions, the issues involved are often contested. While we cannot ultimately decide what is politically acceptable in a technical process, we do provide evidence and reasoning to support the choices that inevitably have to be made in deciding on future socio-economic trajectories, in the belief that these transparent and reasonable arguments provide an acceptable method for exploring future scenarios. In order for the results to be most useful to government, business, labour, and non-governmental organizations, the analysis and the results must take into account relevant socio-economic contextual information and be relevant to existing and future interest groups, including the large percentage of the population that is currently unemployed and/or living below the poverty line, future generations currently in the schooling system, and future generations not yet born. Decision makers need reliable information to understand the connections and inter-relationships between socio-economic characteristics, deep reductions in GHG emissions and development priorities. As such, this report has five principal objectives:

1. To characterize the socio-economic context, and to identify and provide a plausible quantitative description of two possible socio-economic futures.
2. To identify the necessary measures for South Africa to achieve deep decarbonization of the energy system¹ by 2050, within the identified socio-economic futures.

¹ More than 70% of South African GHG emissions are from the energy system or related industrial process emissions (DEA, 2014); as such these are the focus of this analysis and report.

3. To define the suite of technologies, efficiency improvements, socio-economic structural changes, and policies that enable South Africa to simultaneously achieve multiple climate and development objectives, including providing quantitative descriptors of the economic, energy system and emissions pathways.
 4. To demonstrate that South Africa could make a contribution to reducing global GHG emissions in the range necessary to achieve the 2°C goal, which would be fair to the country, while maintaining a South African resident-centered, development-first approach.
- The South African dashboard, DDPP country report, and analysis within, are meant to inform both the scientific and policy communities and provide input to the DDPP global synthesis report.

1.2 Research Approach

As a fundamental principle, this research focuses first on meeting the reasonable needs of all South African residents,² while also making a fair contribution to global GHG emissions reduction consistent with achieving the 2°C goal. This framing is essential due to South Africa's extreme and persistent poverty and inequality. Thus, this analysis focuses on the impacts of future development and decarbonization pathways on South African residents, with a focus on unemployment and income distribution. In addition, a companion project has been launched, the DDPP Political Economy project, which will provide a supporting analysis of how political and institutional interests in South Africa approach the aims identified in the DDPP country report pathways. The Political Economy project will refer to this DDPP country report and is planned to report within 2015.

The South African country team utilized a partially linked economic and energy model and national statistics. The Energy Research Centre (ERC) has spent decades researching energy, the economy and society, and constructing energy and economy models, which include emissions. The energy model, along with a computable general equilibrium (CGE) model with additional functionality especially built in for the DDPP analysis, is used to inform this state-of-the-art energy-economy-emissions policy analysis.

While the linked economic and energy model plays a central role in defining the pathways, background research into credible and plausible economic pathways played an important role in providing inputs to the economy and energy-system modeling phase. This involved research on the social and economic dynamics in South Africa, including economic history, to formulate economic pathways that would plausibly meet the chosen key development imperatives of acceptable income distribution and social inclusion through employment in the formal economy. In addition to Energy Research Centre expertise, the team consulted with a number of leading economists and economic modelers to discuss the constraints and possible solutions to the challenges involved. The South African country team research attempted to achieve development imperatives, whilst also providing an energy system that complied with the 14 Gt CO₂-eq emissions constraint, and this formed a key innovation of this research project.

² The term resident is used to encompass South African citizens, as well as all people that are resident or are likely to be resident in South Africa, as all these people will require at least basic infrastructure and services.

2 The South African Context

As mentioned earlier on in the report, South Africa has a number of persistent development problems and key challenges that need to be overcome in order to achieve acceptable levels of development. This section provides a brief economic history, description of key indicators, and an explanation of South Africa's current socio-economic status to provide some context for scenario building that follows in section 3.

2.1 Economic History of South Africa

While there are inequalities in income levels to some degree in all countries, the intensity of income inequality in South Africa is unusual (Figures 1, 2, 3). Compared to other DDPP countries, South Africa has by far the lowest proportion of income held by the poorest 40% (Figure 2), as well as the highest proportion of

income held by the wealthiest 10% (Figure 3). This is relevant when assessing measures to reduce inequality in South Africa, as the degree of difference between South Africa and other countries suggests that measures used in other countries might not be applicable to South Africa. In formulating future economic scenarios, it is important to understand the impact of historical conditions and drivers on the current levels and trends of key socio-economic indicators. Despite the establishment of a democratic government in 1994 after the demise of apartheid, there have been persistent difficulties in integrating the marginalized into the formal economy (Figure 4) by, e.g., creating sufficient new jobs and/or reducing the large proportion of the population living below the poverty line. Without transforming the historical conditions and drivers, it is unlikely that this will change. Thus, in formulating the

Figure 1. South African Gini coefficient compared with the other DDPP countries

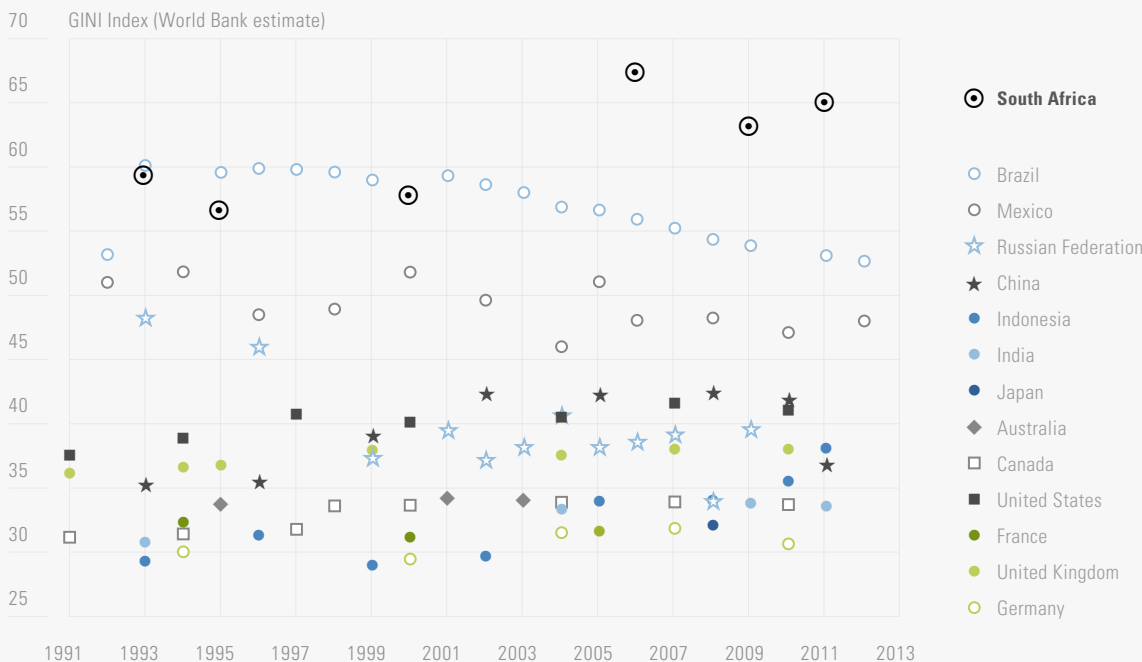


Figure 2. Income share held by poorest 40% of population in DDPP countries

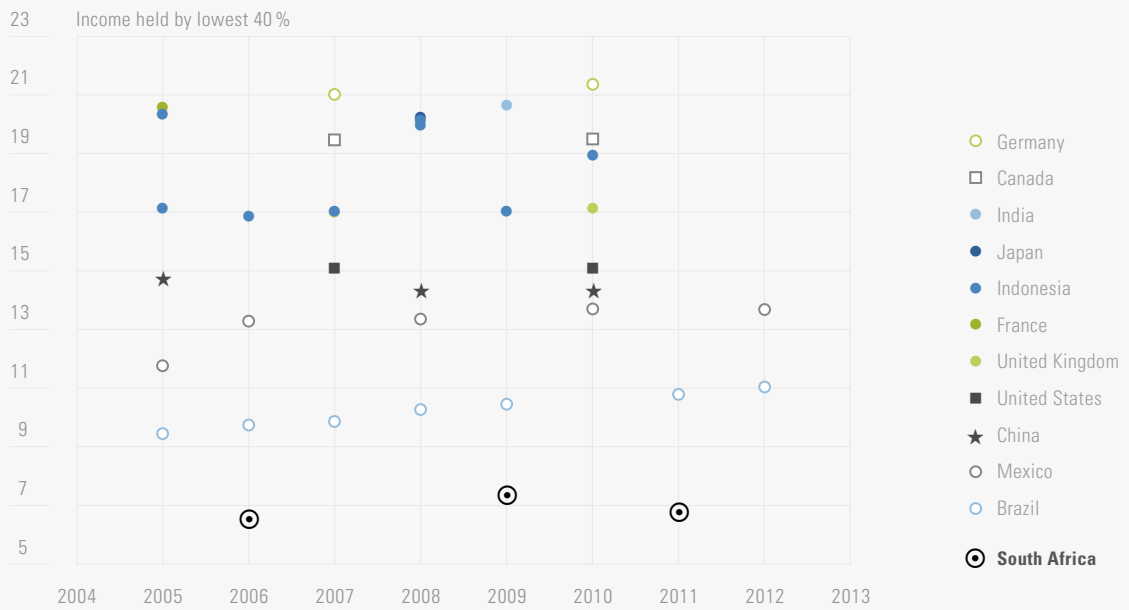
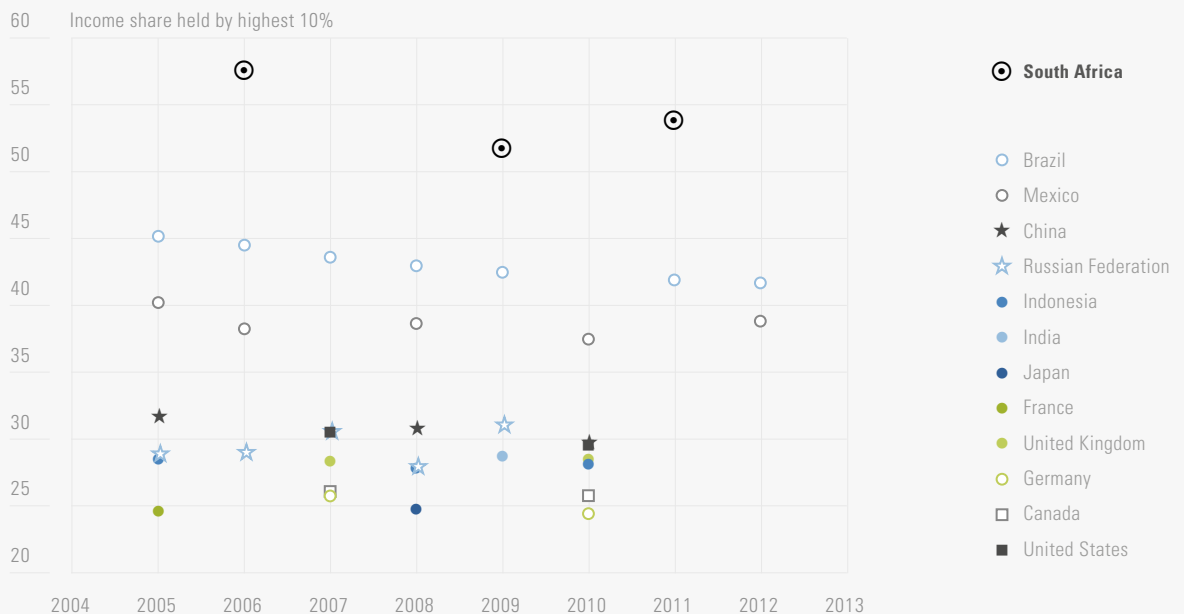


Figure 3. Income share held by the wealthiest 10% of the population in all DDPP countries



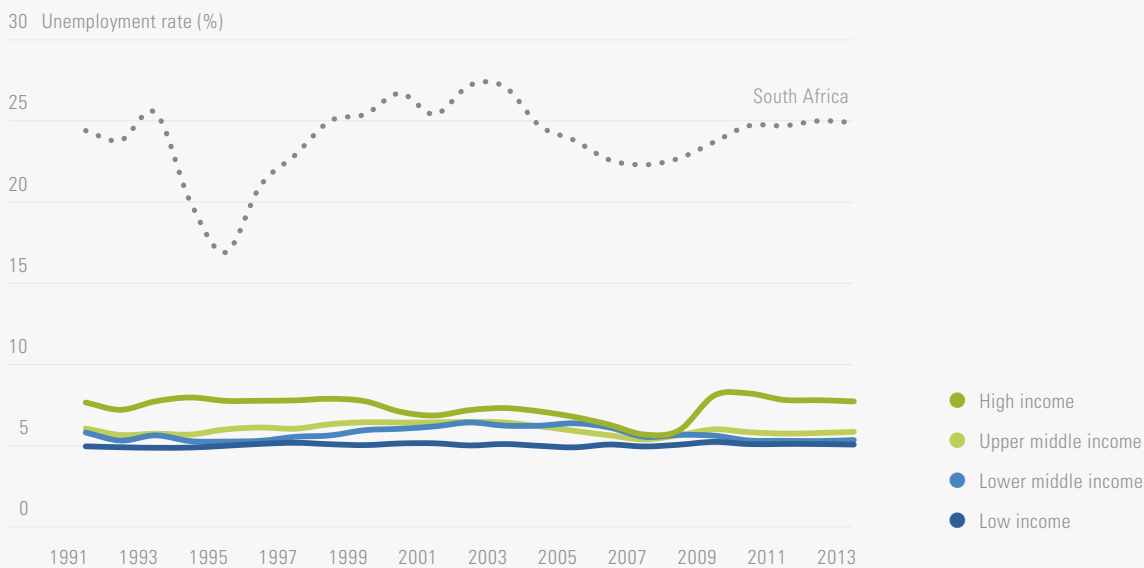
scenarios, we identify and target key sectors and drivers in the economic model in an attempt to achieve improvements in future trajectories with respect to income equality, poverty, skills and employment.

Our analysis relies mainly on a general history of South Africa by Giliomee and Mbenga (2007), recent papers focusing on South African economic history (referenced below), the current structure of the economy and employment, current economic and industrial policy, and a detailed analysis of the performance of South Africa's primary and secondary schools system. This section is not meant to go into these references in depth but to extract key observations and conclusions that provide some explanations of the main underlying causes of the socio-economic challenges. These explanations support the analysis and choices we make in formulating the South African DDPP future socio-economic trajectories. It is most important to note that the credible socio-economic

futures are chosen to illustrate ranges of what might be possible, the associated challenges faced, and to provide inputs for modeling an energy system consistent with these socio-economic futures. Many other futures are possible, and we have attempted to provide a range that illustrates the important features relevant to deep decarbonization pathways.

Many of the current issues involving inequality, poverty, skills, unemployment, and the structure of the economy have their roots in the "minerals-dependent enclave economy" (Natrass 2011) that developed in South Africa over the 20th century. These challenges are the legacy of the capital- and energy-intensive mining, minerals beneficiation and heavy manufacturing core economy, which relied on low-skilled and low-paid labour for its development. In addition, many of the drivers and resultant distortions of establishing and maintaining this socio-economic structure remain.

Figure 4. South African unemployment rate (not including discouraged work seekers; StatsSA 2014) as compared to the average unemployment rates of other countries as grouped by income



Source: World Development Indicators (data modelled by the International Labour Organisation). Available at: <http://data.worldbank.org/data-catalog/world-development-indicators> (Cited from Natrass 2015).

Drawing on Karshenas (2001), Nattrass & Seekings (2015) point out that South Africa is similar to many African countries in having a high land-to-labour ratio, and that similarly, from early on, industrialization in South Africa faced problems in sourcing labour. Coercive measures were institutionalized by establishing a racially-based migrant labour system involving a permanent labouring class (Giliomee and Mbenga, 2007) in parallel with a largely skilled and foreign labour-system supporting the capital-intensive mining sector. The basic principles of the underlying socio-economic system were extended and intensified in the early 20th century in the gold-mining industry. The South African Native Affairs Commission (SANAC) (1903-1905), recommended that “blacks be denied access to ‘white’ land”, and “proposed segregated townships and education for blacks appropriate for lower-level jobs” (Giliomee and Mbenga, 2007:226). This was formalized in the Natives Land Act of 1913, which defined ‘native areas’, less than 8% of the Union’s land area. Black people were not allowed to purchase or lease land outside ‘native areas’. Thus, cheap labour was provided for the mines and ‘white’ farmers while destroying the independent black peasantry. The migrant-labour system was extended, and an ‘influx control’ system formalized from 1923, leading to a situation by the 1950’s where black people had to have a permit to be in ‘white’ South Africa (87% of the country by area) (Giliomee and Mbenga, 2007:321). These permits were granted conditionally along with job offers, which were almost exclusively low-skilled and low-paid jobs.

In the second half of the 20th century, South Africa began the rapid expansion of its mining economy into a capital-intensive, mining, energy, minerals beneficiation and heavy industry manufacturing economy, with a services sector to match. Under the apartheid system, the conditions that had been established and formalized

up until the 1950’s, including state collaboration with private mining and minerals beneficiation companies, dual education systems, reliance on a marginalized reserve labour pool for low-paid low-skilled labour and foreign high-skilled high-paid labour remained. Although increasingly the ‘white’ descendants of the previous generations of immigrants, beneficiaries of an education system on par with industrialized countries, took up the high-skilled jobs instead of immigrants from Europe. This led to continued inequality, a largely unskilled workforce, large-scale poverty in the “labour reserve”, along with an entire marginalized society in the “homelands”, and shortages of skills, all of which limited the economic growth that could be achieved *via* capital-intensive measures.

The relevance of this history to issues facing South Africa today is that these drivers and conditions are unlikely to change rapidly, and therefore are a constraint on possible future scenarios. There exists a divided labour force with a chasm separating a large reserve pool of cheap unskilled and under-employed labour living in communities marginalized from the mainstream economy on one side, and a shortage of skilled labour on the other. Further, there is collaboration between concentrated heavy industry and the state to stimulate capital intensive, high-wage high-GDP-growth economic development, which has not effectively incorporated the large pool of low-skilled labour.

In addition to ensuring the supply of cheap low-skilled labour, the affected population was deliberately kept low-skilled as evidenced by stated education policy. The SANAC proposal of “education for blacks appropriate for lower-level jobs” was implemented, and by 1952 only 3% of blacks had received post primary school education, mainly from church and mission schools, whereas 40,000 whites graduated annually from a full secondary education, mainly from government schools (Giliomee and Mbenga, 2007:319).

The legacy of the resultant very poor skills profile in South Africa persists, both in the products of that system, and in the inability of post-apartheid educational reform to adequately address the depth of the problems in the primary and secondary schooling systems. The first of three distortions Black (2012) mentions in his analysis of unemployment and industrial policy in South Africa is the “historical, systematic undermining of black education” and “what can be generously described as a ‘false start’ in the rehabilitation of black education and artisanal training”.

South Africa participates in a number of international tests of educational achievement that provide data on how effectively the primary and secondary education systems are performing. Important overall features of the system are that in 2013 only 50% of the pupils starting school wrote the final National Senior Certificate (NSC) exam, 40% passed the exam and 12% received an adequate grade in the final exam to qualify for university (Spaull, 2013). As far as the quality of the education leading up to the exam is concerned, the TIMSS³ study showed that in 2011, in the Grade Nine mathematics and science test “a third of pupils performed worse than guessing on the multiple choice items (i.e., no better than random). Furthermore, three quarters of Grade Nine pupils in 2011 still had not acquired a basic understanding about whole numbers, decimals, operations or basic graphs” (Spaull 2013: 4). This is the lowest level of all participating countries. The SACMEQ⁴ study reported a 27% illiteracy rate for Grade Six pupils. Comparison of the results of the 2000 and 2007 SACMEQ studies indicated that literacy and numeracy levels have remained constant over time. Spaull (2013: 6) states that: “Analysis of every South African dataset of educational achievement shows that

there are in effect two different public school systems in South Africa. The smaller, better performing system accommodates the wealthiest 20-25% of pupils who achieve much higher scores than the larger system which caters to the poorest 75-80% of pupils. The performance in this latter, larger category can only be described as abysmal.”

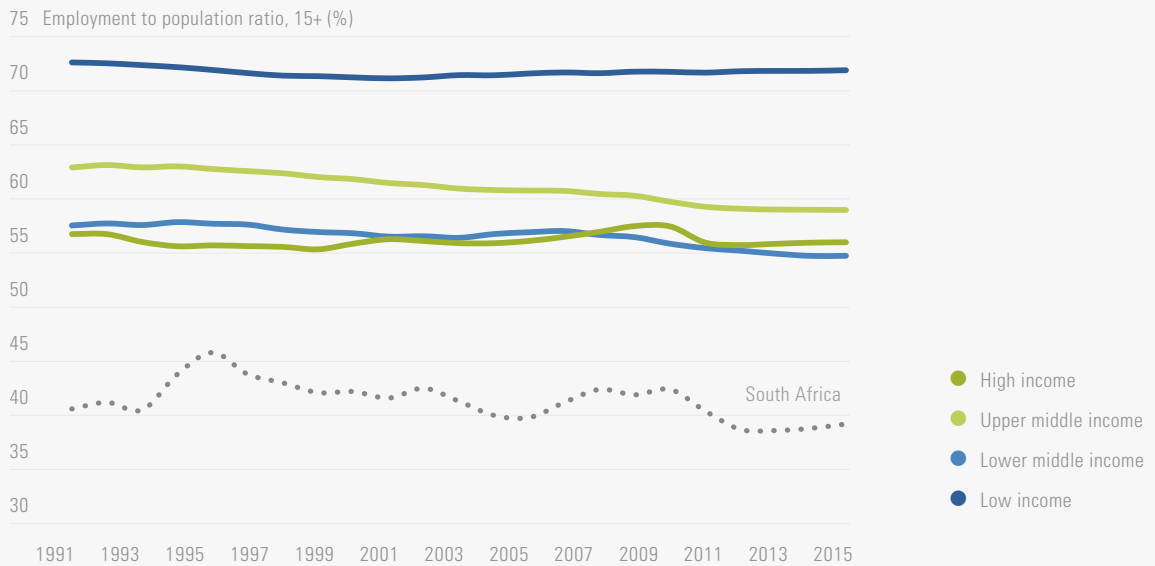
The overall conclusion drawn is that the national primary and secondary schooling systems continue to produce two separate outputs: a minority of pupils who are fit to be trained for skilled jobs or further education and a majority who are not taught the basics in their early years, and from then on are almost pre-determined to join the unemployed or work in low-paid unskilled jobs. The performance of the education system will be a crucial determinant of the future South African skill profile and assessing what is possible or likely in the evolution of the skills profile of this workforce is essential in formulating future socio-economic scenarios. The education system will have to change fundamentally before it can change its performance. The evidence suggests that this change has not been forthcoming and moreover that while some analyses of the problems are emerging, no credible solutions are on the table. The huge inertia in the system, consisting mainly in the existing teaching staff and absence of systems to change this, and the lack of evidence of change in the performance of the system has led to at least one socio-economic future having to consider that the system will continue, as will the resultant education and skills profile in the population.

South Africa is an outlier in terms of its absolute level of employment, some 20-25% below all other countries (Figure 5), and in a cross tabulation analysis is placed “in a small group of

3 TIMSS stands for Trends in International Mathematics and Science Study, PIRLS stands for Progress in International Reading and Literacy Studies.

4 SACMEQ stands for Southern and Eastern African Consortium for Monitoring Educational Quality.

Figure 5. Employed population as a proportion of population aged 15+ years for South Africa, and the averages for other countries categorised by income



Source: World Development Indicators (data modeled by the International Labour Organisation). Available at: <http://data.worldbank.org/data-catalog/world-development-indicators> (Cited from Natrass 2015).

otherwise war-torn countries that perform poorly...Economic growth is inhibited, and poverty persists" (Natrass & Seekings 2015: 5). Indeed, Natrass & Seekings (2015) state that: "Bosnia and Herzegovina, Bulgaria, Iraq and South Africa share the dubious distinction of relatively high unemployment rates and relatively low employment elasticities. This means that in the absence of a fundamental change to the growth path, these countries are unlikely to grow their way out of their unemployment crisis any time soon." Natrass (2011: 5) in analyzing the period 1990-2010 observes that average remuneration rises steadily, in real terms, and that labour productivity rose even faster: a "success" for high-wage, high productivity growth by the traditional South African economic structure. However, over the same period, employment contracted. Based on this she makes the important point that: "employed workers and capitalists benefitted at the cost of those who lost their jobs, or who were

hoping to obtain work." She also uses this as an example of how successful implementation of a policy of high-growth, high-productivity within the existing South African economic structure did not create the necessary jobs over this period. As such, South Africa has a unique history involving the high ratio of skilled to unskilled labour, state support for capital intensive processes, and shortages of skilled labour resulting from racial restrictions on hiring and state education policies.

In summary, Natrass and Seekings (2011, 2015) and Black (2012) provide convincing data and analysis that key conditions and drivers that first appeared at the beginning of South Africa's industrialization, and intensified over the 20th century, have still been operating in the past two decades, and that their subsequent impacts remain. Independent analysis of key indicators of education system performance, levels of equality, poverty and employment demonstrate that the extreme

and outlier status of these indicators inherited from the colonial and apartheid eras remain. The analysis of the education system indicates that at least another generation of children will emerge from 12 or more years of schooling very poorly educated, most pre-determined from the first years of schooling for unskilled work. Nattrass & Seekings (2015) provide convincing analysis that shows that recent 1990-2012 socio-economic trajectories are a result of the persistence of similar drivers to the past and that it will be necessary to change these to achieve different outcomes. Black (2012: 6) notes that "the challenge for South African industrial policy, therefore, is to tilt the playing field to favour labour absorbing growth in order to mobilize the huge potential of an underemployed and poorly-skilled workforce." This would not preclude growth in the sectors previously advantaged by policy. It means withdrawing special support from these sectors and re-directing this support to subsidizing labour and training and encouraging more labour-absorbing investment. Consideration of the relevant features of past conditions and drivers and current conditions and drivers and their impacts are an essential input to modeling future pathways presented in the next sections.

2.2 South Africa's Current Socio-Economic Status

It is officially acknowledged in the latest key policy documents, namely the National Development Plan (NDP) (NDP, 2012)⁵ and the New Growth Path (NGP) (NGP, 2011), that poverty, inequality and unemployment remain severe. Indeed, the NGP Frameworks begins with

"Chapter 1 - The core challenge: mass joblessness, poverty and inequality". These issues are highly relevant as all GHG mitigation approaches must consider economic policies and planning.

The South African population was 52 million people in 2011 (StatsSA 2011 Census), with 60% living in urban areas (NPC 2011b). The population grew 21% between the 1996 and 2011 censuses, and the NDP identifies rapid urbanization as a major challenge: South Africa will need to make provision for 8 million new urban residents by 2030 (NDP, 2012).

South Africa is an upper middle-income developing country with a gross domestic product (GDP) per capita of R73,715 per person (at current prices; SARB; US\$5,941 in US\$ at current exchange rate of 0.08 US\$/ZAR). There is a modern urban economy, with an advanced service sector and an energy-intensive industrial base reliant on large domestic mineral resources, co-existing with large-scale poverty. South Africa has made substantial progress in its first 20 years of democracy, including in poverty reduction, with the most dramatic improvements including large increases in access to basic services in communities that were deliberately excluded by apartheid (e.g., access to water has increased from 60 to 95% of households, access⁶ to electricity has increased from 50 to 90% of households, and the proportion of people in formal housing increased from 64 to 78%) (Twenty Year Review, 2014). However, there remain high levels of inequality, and society is largely still divided along spatial, economic, and social lines established in colonial and apartheid eras. Annual average growth from 2003 to 2008 was 4.6% per year, until 2008 when the global financial crisis negatively impacted economic growth

⁵ The National Development Plan was drafted by the National Planning Commission and offers a long-term perspective on the future of South Africa. It envisages a desired destination and identifies the role different agents in the economy should play to achieve the end goal of the elimination of poverty and a reduction of inequality by 2030.

⁶ Access in this sense means "connected to". Since the early 1990's a large-scale electrification programme has extended connections from a third of houses to 90%. However, many connected houses cannot afford to pay to use electricity for much more than basic lighting and energy poverty remains extensive, meaning that effective access to electricity remains constrained by income poverty.

in a large portion of the globe, including South Africa. GDP growth has averaged 1.9% since 2008, a value significantly below the development goals set out in the NDP, which specifies at least 5% per year (NDP, 2012). Projections of growth for beyond 2014 have continuously been revised downwards (currently at 2.1 % for 2015; IMF WEO, 2015), which is typically attributed to continued labour unrest and low global commodities prices, as well as slow growth in key trading partners and power shortages.

In 2011, the proportion of the South African population living below the nationally established Lower-bound Poverty Level (R416 per month in 2009 prices) was 32.2%, while the proportion living below the Upper-bound Poverty Level (R577 per month in 2009 prices) was 45.5% (StatsSA, 2013a⁷). The poverty gap⁸ is estimated to be 19.6% for South Africa, which provides a sense of the minimum social transfer cost needed to eliminate poverty (World Bank, 2013). To alleviate the most severe effects of poverty, social grants⁹ are currently extended to 16 million people (AfricaCheck, 2015), which is a steady increase from 3.8 million people in 2001 (Gumede, 2013).

According to the 2011 census, unemployment was 28.9% (StatsSA, 2014). However, if the category 'discouraged work seekers' is included, the unemployment rate is closer to 40% (Gumede, 2013). Unemployment in South Africa has been persistent and structural, as discussed in section 4.1; indeed South Africa is an outlier in global statistics. These issues present challenges for formulating plausible solutions. The South African government routinely states that addressing unemployment is a high

priority (NDP, NGP, etc.). Economy-wide analysis using a CGE model, suggests that unemployment could be reduced to as low as 12% by 2025 by reducing infrastructure gaps, easing the skills constraint, and increasing investment (Faulkner *et al.*, 2013). The analysis highlights that the shortage of skilled labour prevents economic expansion, if the current economic structure is maintained, and decreases opportunities for unskilled labour. Faulkner *et al.* (2013) state that the keys to reducing unemployment and increasing income include a sustainable increase in the employment intensity of the economy, increased savings, foreign direct investment and domestic investment, and the removal of incentives that favour capital-intensive and not labour-intensive industries.

All strategies to alleviate unemployment mention the importance of fostering overall economic growth. Economic growth is often considered the first step in sustainable poverty alleviation, as well as a key component of improving education, increasing life expectancy, strengthening democracy, and reducing crime (Akinboade and Kinfaek, 2013). However, the relationship between GDP growth and development is weak in South Africa (see section 4.1), and indeed there are a number of concurrent socio-economic requirements. The existing NDP and NGP assume a very high GDP growth rate and, although they highlight a number of goals and achievements to 2030, they do not outline how these goals will be achieved. Fundamental goals set in the NGP in 2011, such as "5 million new jobs to be created" by 2020 (NGP, 2011), show no sign of being realized. Based on the policy's stated reliance on GDP growth above

⁷ Statistics South Africa publishes these levels and the methodologies for determining them annually, see StatsSA 2014.

⁸ The poverty gap is defined as the percentage of national income needed to bring everyone up to the poverty line.

⁹ In 2015 grants are: R1,410 for pension, R1,410 for disability, R860 for foster care, R330 for child support. The multifaceted nature of poverty cannot be adequately captured in the financial figures and monetary poverty levels. For example, the context for child support grants should be seen in the light of Unicef (<http://www.hst.org.za/news/south-africa-has-most-aids-orphans-un>) estimating that 2.5 million South African children under 18 had lost at least one parent due to any cause, with about 450,000 having lost both parents. HIV/AIDS is the main cause with infection rates in women between 30 and 34 years old being 36% in 2012, over 400,000 new infections occurring, and a total of some 6.2 million people living with HIV/AIDS in South Africa in 2012, see Shisana *et al.* (2014).

5%, with growth rates to date and GDP prospects, achieving these goals is not likely. In fact, in the international context of a general recovery from the 2007/8 global recession, the South African GDP remains stubbornly low, with a quarter on quarter contraction in 2014 (StatsSA 2014). In the twenty-year period from 1994 to 2014, the South African labour force increased from 11,386 million to 20,122 million (77%), while unemployment increased from 2,289 million to 5,076 million (103%) (StatsSA 2014). This again suggests that alternative future trajectories based on changes to the structure of the economy are required.

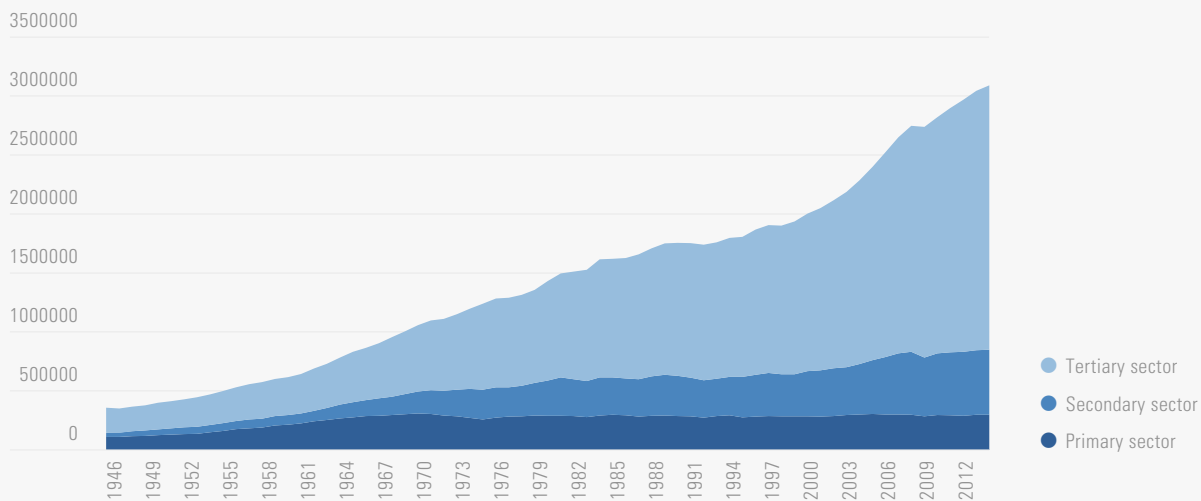
2.3 Economic Structure and the Role of Emissions Intensive Sectors

Throughout the 20th century the South African economy shifted from a primarily rural, agricultural economy, to an urban, industrial economy. This shift was initially based on mining, followed by a transition to an energy-intensive, minerals-based industrialization economy based on coal and imported crude oil. Over the past 20 years, South Africa has been steadily transitioning towards an

economy dominated by the tertiary sector, which has increased from 57% of GDP in 1984 to 70% today (Figure 6). Despite the growth and current size of the tertiary sector, there are persistent structural features in the economy and labour markets linked to the history of development in the primary and manufacturing sectors. One aspect of this structure is that while the primary and secondary sectors only account for 30% of the economy, there are many inter-linkages between these sectors and the tertiary sector. In addition, the economy relies on the primary and secondary sectors for foreign direct investment and foreign exchange export earnings. Mining, minerals and secondary beneficiated products account for almost 60% of export revenue (NPC 2011).

A further set of structural features relate to the specific social mechanisms used to develop the mining and heavy manufacturing (i.e., minerals beneficiation) sectors, which are chronicled in more detail in the previous section, due to the deep-rooted nature and unique challenge they present to issues related to economic and social development. These features remain beyond the 1994 democratic transition, and need to be

Figure 6. Structure of South African economy 1946 - 2012 in million ZAR 2010



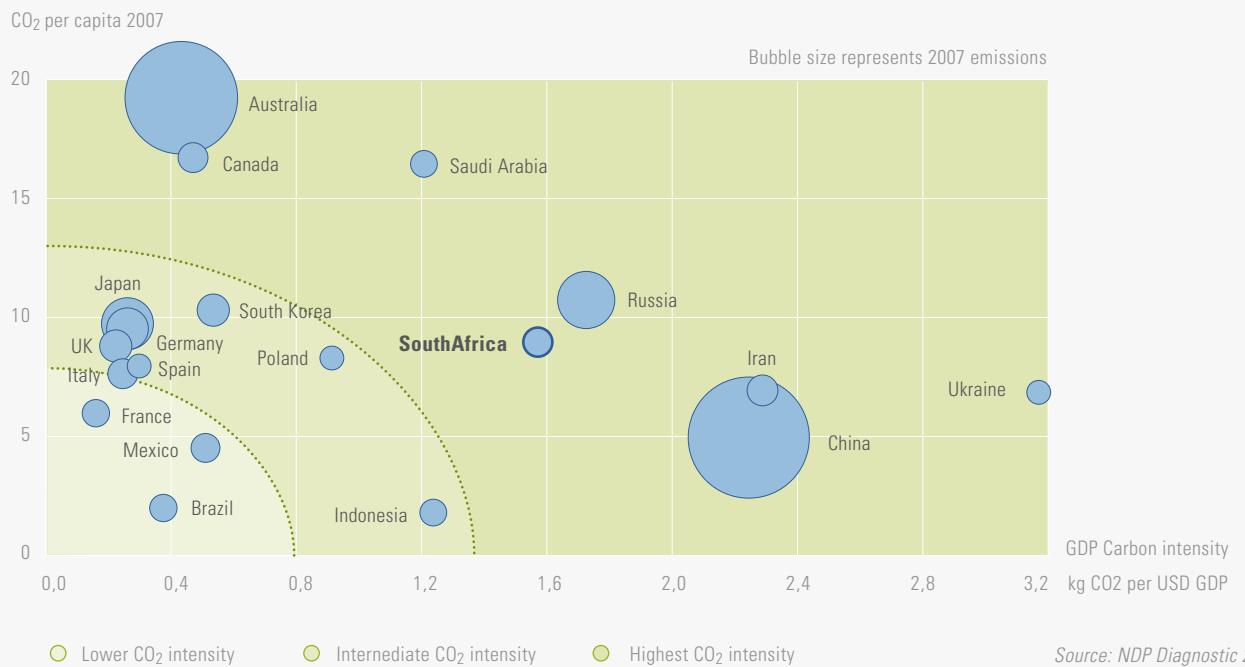
considered when formulating and assessing potential future scenarios.

The energy- and emissions-intensive sectors, including the sectors that dominate exports (i.e., mining, minerals, etc.), are also inter-linked with the history and structure of the economy. As a result of development over time in these sectors, South Africa has relatively high emissions per capita, as well as emissions per unit GDP (Figure 7). This high degree of energy intensity in the economy, combined with persistently high levels of inequality, poverty and unemployment detailed in the previous sections, presents challenges to formulating and assessing potential economic and emissions scenarios for South Africa.

South Africa has extensive mineral resources that drove economic growth in the 20th century, but

economic growth did not lead to reductions in inequality. Coal still accounts for South Africa's largest export and provides 90% of electricity generation. South Africa's recoverable coal reserves amount to approximately 49,000 Mt, giving the country the world's sixth-largest coal reserves (SACRM, 2013) and a reserve/production ratio of more than 200 years. However, the associated GHG emissions are a serious problem. South Africa also has excellent renewable resources estimated at 548 GW of potential for concentrated solar power (CSP; Fluri 2009). Hageman (2013) estimates wind potential at 56 GW, or 157 TWh per year. There is also a large regional hydro potential, greater than 40 GW.¹⁰ The sections below look into these issues in more detail, providing a background for formulating and assessing credible future scenarios.

Figure 7. Emissions intensity per capita vs. emissions intensity of GDP



¹⁰ Most energy-related figures in this chapter, including energy GHG emissions, are estimated based on: (i) DOE 2006 statistics which are the latest available official statistics covering all energy subsectors and related time series from 1992-2006; (ii) Eskom statistics published in the Eskom annual report; and (iii) where public data is not available, estimates are made based on work by the Energy Research Centre (ERC) at the University of Cape Town (UCT) related to the SATIM energy and emissions model. see <http://www.erc.uct.ac.za/Research/esystems-group-satim.html>

3 Construction of Socio-Economic Scenarios and Modeling Methodology

3.1 Characteristics of Future Scenarios

The development challenges outlined above are serious policy problems that need to be accounted for in all GHG reduction plans. Conversely, the South African government acknowledges the importance of sustainable growth and environmental protection in key economic growth-related policies such as the National Development Plan. This recognition is two-fold as South Africa is a significant contributor to global GHG emissions, but as a developing country South Africa is also particularly vulnerable to the effects of climate change on health, water availability, and food production. The main research question addressed here focuses on the development of socio-economic pathways that achieve development imperatives and a carbon constraint consistent with mid-PPD (i.e., 14 Gt energy sector CO₂-eq cumulative through to 2050) for South Africa. The background research on South African economic history and current socio-economic features informed thinking on devising plausible development-first low-carbon scenarios.

Fundamental to our analysis of credible future socio-economic trajectories is that the current structure of the economy is not able to absorb the high levels of unskilled labour in the economy. This led to a focus on two approaches, changing the structure of the economy to improve absorption of unskilled labour, and improving the skills profile of the South African labour force through changes to the educational system. South Africa has a number of very urgent and complex development problems. The goal of this work is not to solve all of them, and as a result we have aimed to provide an overall

credible future focusing on developing economic pathways where achieving a significantly reduced rate of unemployment by 2050 is prioritized. It is important to note that although there seems to be consensus that structural changes to the economy are necessary, there is no consensus on how much development metrics could improve, and how these structural changes will be implemented.

Black (2012) suggests unemployment could be addressed by identifying and growing sectors with higher employment potential. Natrass (2011) and Natrass & Seekings (2015) suggest that high-wage, high productivity growth within the current structure of the economy does not lead to reduced unemployment. We take the position that employment and social and economic inclusion in South Africa are key elements for transforming society and achieving development imperatives. Currently some 16 million people out of a population of around 53 million are on social grants (AfricaCheck 2015), and government has stated explicitly that this is not sustainable. Although social grants are essential in the short to medium term to alleviate extreme poverty, a core aim in long-term planning should be lower unemployment rates, sustainable employment, and living wages.

The NDP and NGP are ambitious in both their goals and their growth forecasts. The policies provide a lot of detail on defining development goals, but not enough detail on exactly how these goals are achieved. Given South Africa's history, current economic situation, and economic forecasts, a GDP growth rate of 5-6% annually is very ambitious (Natrass and Seekings 2015). It is important to note that the economic model used in this research does not require

specifying an *a priori* GDP growth rate. Indeed, GDP growth rate is determined endogenously as it is a reflection of the assumptions and exogenous changes made to the economy over the modeling time horizon.¹¹

In addition to published sources, Professor Anthony Black, Professor Owen Crankshaw, and Dr. James Thurlow were consulted on how South Africa might reduce unemployment, and how this could be incorporated into the coupled economic-energy model. One of South Africa's pre-eminent CGE modelers explained in a personal communication¹² that the CGE is a useful tool but that, "there are lots of fundamental questions that need to be addressed *before designing* simulations." Answering these questions has been central to the Phase 2 DDPP approach; which was fundamentally different from Phase 1 where the economic structure and skills profile were left unchanged.

Taking into account South Africa's economic history, and the DDPP focus on reducing GHG emissions, we first identify sectors that could allow us to achieve development imperatives as well as lead to low-carbon growth. We analyze employment multipliers¹³ and carbon intensities to identify key sectors that have high potential for both the employment of unskilled labour and low-carbon emissions. A key component of the first considered scenario is the assumption that no change in the skills profile of the South African labour pool happens over the next decades. A second component of this scenario is the assumption of increased trade in low-carbon sectors, which would benefit South Africa according to research done in the NDP and by Anthony Black and others. This is implemented by ad-

justing world prices for agricultural products and trade elasticities to simulate an increase in 'trade openness' and to increase exports of agricultural products in the CGE. This allows for structural changes to occur endogenously in response; demand is spurred in the economy without an unintended fall in the price of these goods to below-market value. These changes represent one scenario in the coupled economic-energy modeling, which is hereafter referred to as the Economic Structure Scenario.

The second scenario focuses on the impact of reforms to the educational sector, which as discussed above, continually underperforms leaving young South Africans without the skills needed to participate in the economy. This scenario, hereafter referred to as the High Skills Scenario, considers exogenous improvements to the educational sector such that by 2030 higher skilled labour starts becoming available to enter the economy. An increase in the openness of the economy as simulated in the Economic Structure Scenario is not included in the High Skills Scenario. Any structural change that may occur in the High Skills Scenario is the result of an increase in the supply of high skilled labour and the subsequent demand driven by an increase in employment.

3.2 Modeling Methodology

The Energy Extended South African General Equilibrium Model (e-SAGE)

The e-SAGE model is a dynamic recursive computable general equilibrium (CGE) model developed by UNU-WIDER (Arndt *et al.*, 2011). The main input is the 2007 South African Social Ac-

¹¹ The main drivers for GDP growth in the CGE model are factor productivity rates, the availability of savings and investment and population through labour supply.

¹² James Thurlow, January 2015 – personal communication.

¹³ Employment multipliers refer to the direct and indirect effects on employment of an increase in growth in a given sector. We calculated the employment multipliers by skill level (unskilled, semi-skilled and skilled) for each sector in the economy.

counting Matrix (SAM). The SAM is a set of accounts that represents all of the productive sectors and commodities in South Africa, as well as factor markets, enterprises, households, and the 'rest of the world.' The 2007 SAM has 61 productive sectors (industries) and 49 commodities. The seven factors of production include land, four labour groups disaggregated according to level of education¹⁴, and there is a distinction between energy and non-energy capital (Arndt *et al.*, 2013). The government, enterprises, 14 household groups based on their per capita expenditure, and the 'rest of the world' are all represented (Thurlow, 2004). The behavior of industries and households is governed by rational expectations (Thurlow, 2008). Industries and producers aim to maximize profits while households aim to maximize their utility subject to their budget constraint. Product and factor market equilibrium are maintained. The e-SAGE model is a dynamic recursive model, and as such has two periods, the within-period and the between period. The static part of the CGE model makes up the within period. Some variables and parameters are updated during the between period, with capital accumulation and re-allocation being determined endogenously with exogenous forecasts for population growth, factor productivity and technical change in the energy sector (Alton *et al.*, 2014). A key feature of the e-SAGE model is that non-energy industries can react to energy price changes during the between-period by shifting their investments to less energy intensive capital and technologies, the ease of which is specified exogenously (Alton *et al.*, 2014)¹⁵. It is important to note that some exogenous changes made in the CGE model rep-

licate policy goals in the NDP: achieving a labour participation rate of 65% by 2030, an increase in South Africa's agricultural exports, and an increase in national savings to 25%.

We increased the level of investment in the economy in order to drive demand and ultimately growth to 2050. In more technical terms, we increased the portion of final domestic demand that comes from investment flows (known as the savings portion of absorption) to 25% by 2025, the savings portion of absorption is ~ 20% in South Africa. This is low compared to other BRICS economies, with the exception of Brazil at 20%: China is at 48%, India is at 35% and Russia is at 25% (StatsSA MDG Goals Report, 2013). There was a positive trend in South Africa from 2001 to 2008, with investment increasing from 14.8% of GDP to 23.1% in 2008. However, since the financial crisis, and with low GDP growth, the South African savings rate has decreased to its current value. In both modeled scenarios, the savings portion of absorption was made exogenous. It starts at 20% in the base year, and then increases to 25% by 2030, in line with the goals of the NDP. The result of this change is to increase the availability of investment, which can drive increases in employment through stimulated economic growth. In its current structure, the South African economy struggles to absorb unskilled unemployed workers. The Economic Structure Scenario aims to change the structure of the economy to one that is more geared to employment and low-carbon growth. An initial analysis resulted in the identification of key sectors (i.e., industries in the CGE model) that had both high unskilled labour multipliers as well

¹⁴ Labour is disaggregated into four groups according to level of education and mapped to level of skill: individuals that have attained primary and middle-school education are considered unskilled, completed secondary school are semi-skilled, and tertiary education are skilled.

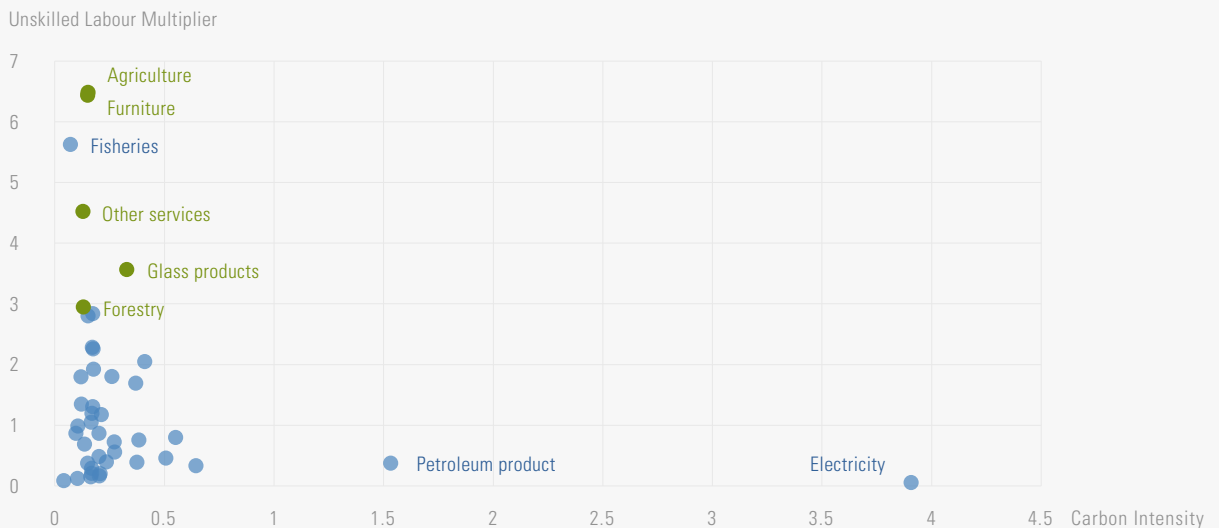
¹⁵ Energy is considered an intermediate input and the interaction between intermediates and factors is governed by a Leontief production function. To decrease the rigidity of using a Leontief production function, there is 'response elasticity' that governs the amount sectors are able to change in their energy inputs per unit of output based on energy prices.

as low-carbon intensities (Figure 8), i.e., agriculture, furniture, glass, forestry and 'other services'. The next step was to incentivize growth in the chosen sectors by increasing their attractiveness and generating a flow of investment toward them. This is done by adjusting the capital productivity of the sector and allowing capital flows to react accordingly. However, the eSAGE model was initially coded to allow the user to change total factor productivity rates and not adjust labour and capital productivity rates in isolation. The model was adjusted to allow an increase in capital productivity without increasing the productivity of labour in a sector. At the same time, the elasticity of substitution between capital and labour was reduced to ensure that those sectors would not switch from labour to capital

because of relative productivity levels. The shock, in this case, was a doubling of capital productivity, which resulted in growth in the chosen sectors accompanied with an increase in employment. This methodology allows the sectors to become increasingly competitive over the period and grow faster than they would have otherwise.

Given the historical focus on growth in high-skilled capital-intensive sectors in South Africa discussed above, promoting growth without changing the skills profile or economic structure is unlikely to reduce unemployment. As such, the second scenario explores reducing unemployment without changing the current structure of the economy. In order to promote improved development metrics in this situation, improvements in education resulting

Figure 8. The unskilled labour multiplier as a function of the carbon intensity of each sector in the e-SAGE CGE model
i.e., the number of jobs that are created (indirectly and directly) through an increase in the production of a sector.



The sectors with low carbon intensity and high unskilled labour multipliers were targeted for growth in the Economic Structure Scenario (green markers).
The fisheries sector was not targeted for growth as the resource constraints on fish stocks and estuaries are not captured in the CGE.
The sectors with the highest carbon intensity are electricity and petroleum products (labelled).

in increases in the skills of the labour pool are required. For the High Skills Scenario, the supply of higher skilled labour was increased exogenously over time. This simulates an increase in access to education and participation of low-income individuals in the economy.

South African TIMES Model (SATIM)

The South African TIMES¹⁶ Model (SATIM) is an inter-temporal bottom-up optimisation energy model of South Africa built around the Markal-TIMES platform. SATIM uses linear or mixed integer programming to solve the least-cost planning problem of meeting projected future energy demand, given assumptions such as the retirement schedule of existing infrastructure, future fuel costs, future technology costs, learning rates, and efficiency improvements, as well as any given constraints such as the availability of resources. SATIM can be run in full energy sector mode (SATIM-F) or in electricity supply only mode (SATIM-E). In SATIM-F, demand is specified as useful energy demand (e.g., demand for energy services such as cooking, lighting, and process heat), and final energy demand is calculated endogenously based on the optimal mix of demand technologies. The full model allows for trade-offs between supply and demand sectors, it explicitly captures structural changes (i.e., different sectors growing at different rates), process changes, fuel and mode switching, and technical improvements related to efficiency gains. The result of the optimization is both the supply and demand technology mix (e.g., capacity, new investment, production, and consumption) that would result in the lowest

discounted system cost for meeting energy demand over the time horizon, subject to all other imposed constraints.¹⁷

The Linked Model SATIM-E e-SAGE

In this model, alternate runs of SATIM-E and e-SAGE are performed from 2006 to 2050, each time exchanging information about fuel prices, electricity demand, investment and capital growth in the power sector, electricity production by technology group, and electricity price. Given an initial demand for electricity, SATIM-E computes an investment plan, and an electricity price projection. These are passed onto e-SAGE to determine the impact, if any, that the new price projection has on the demand, which then goes back to SATIM in the next iteration and after a few iterations convergence between the two models is reached.

Modeling Assumptions Common to All Scenarios

Population growth is based upon recently developed country-specific probabilistic population projections from the United Nations Population Division (Raftery *et al.*, 2012).

A real discount rate of 8% was used in optimization routines for consistency with the South African Integrated Resource Plan (IRP, 2010). Power plant cost and performance parameters were aligned to the IRP update assumptions (IRP Update 2010, 2013), with some updates on the investment cost for nuclear, CSP and PV derived from recent work within ERC (Merven *et al.*, 2015). In e-SAGE, the total factor productivity across all sectors is tuned

¹⁶ TIMES is a well-established partial equilibrium optimization energy modelling platform that was developed by IEA-ETSAP (www.iea-etsap.org) and is widely used by a large number of countries for energy planning and analysis.

¹⁷ Certain behavioural aspects such as speed of adoption of new demand technologies is currently modelled in a fairly simple way via a set of constraints.

to follow historical growth from 2007 to 2014. There are essentially the same productivity assumptions in all sectors, which can then be targeted and shocked to drive structural changes by introducing heterogeneity. In 2015 they are set at 0.92%, and from 2015 onward they decrease by 0.01% annually via an exogenous total factor productivity growth path. The following closures are applied for all of the e-SAGE model runs:

- Savings-invest: Previous studies have found that the savings-driven investment closure is most appropriate for South Africa.¹⁸
- Government: Uniform sales tax rate point changes are allowed for selected commodities, while government savings remain fixed.
- Foreign: South Africa has a flexible exchange rate, therefore a fixed trade balance is assumed and the exchange rate is able to adjust and maintain equilibrium between the payments to and from the rest of the world.
- Labour: A large portion of the low-skilled workforce in South Africa are unemployed, and some of this unemployment is structural. Therefore, it is assumed that low-skilled labour is not fully employed and that there are rigidities in the labour market.¹⁹ Skilled labour is assumed to be fully employed and mobile, growing at 0.6% annually for secondary school educated workers and at 0.5% annually for

workers educated at the tertiary level.²⁰ Factor prices (i.e., rent or wages) are allowed to adjust to ensure equilibrium is reached and demand equals supply. Wages are tracked to ensure they do not go below a prescribed value, which is the same for all industries, as this would be a sign that there was not enough demand to drive employment.

- Capital: Fully employed and activity- or sector-specific.
- Land: Fully employed and mobile, that is, it can be used for different purposes.

Modelling the Carbon Constraint

Initially, SATIM-F is run with a 14 Gt CO₂-eq energy emissions cumulative constraint²¹ using a reference economic growth projection. The resulting CO₂-eq trajectory in the power sector is then imposed onto SATIM-E in the linked SATIM-E e-SAGE model. The socio-economic results of this linked model are then input to the DDPP dashboard. In addition, the linked model generates a new economic growth projection. This is then used as an input to a second SATIM-F run with the 14 Gt cumulative CO₂-eq constraint still applied. The energy sector results of this second SATIM-F run, with the cumulative CO₂-eq constraint and the new economic growth projection, are then input to the DDPP Dashboard.

¹⁸ The relationship between savings and investment continues to be a highly debated and controversial topic in macroeconomics (Nell, 2003). Neo-classical along with new endogenous growth theory maintains the view that it is former savings that decide an economy's investment and output (Thurlow, 2004). Conversely, from a Keynesian perspective, it is investment that is exogenous and savings that adjust accordingly (Thurlow, 2004). Although, according to Nell (2003), recent works have established that in the case of South Africa, the long-run savings and investment relationship is associated with exogenous savings and no feedback from investment. In light of this, the SAGE model assumes a savings-driven closure (Arndt, Davies, & Thurlow, 2011).

¹⁹ To simulate unemployment, an upward sloping supply curve was assumed for low-skilled labour. Low real wage supply elasticities were also assumed to indicate that their unemployment is structural.

²⁰ In the High Skills Scenario (Scenario 2), there is a point change acceleration for skilled and high skilled, 3% and 2% respectively, post-2025. This simulates an increase in skilled portion of the labour force (e.g., better education and training).

²¹ The cumulative constraint spans the period 2015 to 2050. It includes energy sector emissions and also some non-energy sector emissions, including fugitive emissions from coal and gas extraction, gas transportation, and production of liquid fuels from coal. It excludes process emissions from industrial processes and other non-energy sector emissions (e.g., AFOLU).

4 Results

The results of the linked e-SAGE CGE and SA-TIM energy system modeling are first presented with respect to what extent development imperatives are met in the two scenarios. This is followed by a description of what energy sector supply changes as well as technology changes on the demand side are required to meet the 14 Gt cumulative CO₂-eq emissions constraint, and how those differ in the two socio-economic scenarios. Key outcomes for the economic and energy sectors are presented in (Table 1) for the base year of 2010 and the final year 2050 for both the Economic Structure Scenario (Scenario 1) and the High Skills Scenario (Scenario 2).

4.1 Economic Results

To briefly summarize, there were two scenarios represented in the e-SAGE CGE model, which were both linked to a GHG emission constrained energy system model. The goal of both scenarios was to reduce unemployment. The approach in the first scenario was to identify an economic structure that decreased unemployment while remaining within the emissions constraint. The approach in the second scenario was to simulate a large improvement in the overall skills profile of the working population, which would require a significant improvement in the effectiveness of the education sector, including training and

Table 1. Key metrics for the Economic Structure (Scenario 1) and High Skills (Scenario 2) scenarios in 2010 and in 2050.

Indicator	Units	2010	Economic Structure 2050 Scenario 1	High Skills 2050 Scenario 2
Population	Millions	51.5	62.3	62.3
GDP per Capita	Real US\$ 2005/person	4 825	12 973	12 294
Unemployment	%	24	12	18
Population in Low-Income Bracket	%	50	18	17
Persons per Vehicle	Person/vehicle	10.2	5.6	5.7
Final Energy Consumption	EJ	2.48	4.75	4.58
Annual GHG Emissions	Mt CO ₂ -eq	398	241	242
Per capita total GHG emissions	Tons CO ₂ -eq/cap	7.7	3.9	3.9
Energy Intensity of GDP	TJ/Million US\$ 2005	10.0	5.9	6.0
Levelized Cost of Electricity	US\$/kWh*	0.056	0.110	0.106
Electricity Generation				
Coal	%	91.8	0	0
Natural gas	%	0.2	5.7	6.1
Nuclear	%	5.5	0	0
Hydro	%	2.1	1.6	1.7
Wind On-Shore	%	0	15.8	16.6
Solar PV	%	0	13.0	13.0
Solar Thermal	%	0	62.5	61.2
Biomass	%	0	1.3	1.4

* In 2010 Rands, the LCOE in 2010 is 0.504 ZAR/kWh and in 2050 for Scenario 1 it is 0.994 ZAR/kWh and for Scenario 2 it is 0.955 ZAR/kWh.

vocational development programs. The results of the two scenarios, identified as the Economic Structure Scenario, or Scenario 1, and the High Skills Scenario, or Scenario 2, respectively, are discussed below.

The economy grows from a GDP of US\$ 248 million²² to US\$ 808 and 765 million in the Economic Structure Scenario and the High Skills Scenario, respectively (Table 1). GDP per capita increases over time, with Scenario 1 increasing at a faster rate from ~2030 through to 2050 (Figure 9). Population is exogenous in the model, and the same population is used for both scenarios, hence increases in GDP per capita over time occur solely due to GDP changes over time. The economy averages 2.8% annual GDP growth in Scenario 1 and 2.6% annual growth in Scenario 2 from 2010 to 2050 (Figure 10).

The GDP growth rates presented here are lower than the growth rate of 5.4% in the National Development Plan (NDP) and the 4 to 7% in the New Growth Path (NGP), both of which are targeted at these levels to achieve employment

growth. It should be noted that the NDP time horizon is through 2030 while the NGP reflects even shorter-term growth through to 2020. GDP growth is endogenous in the e-SAGE CGE model,

Figure 9. GDP per Capita Average Annual Growth Rates by Decade

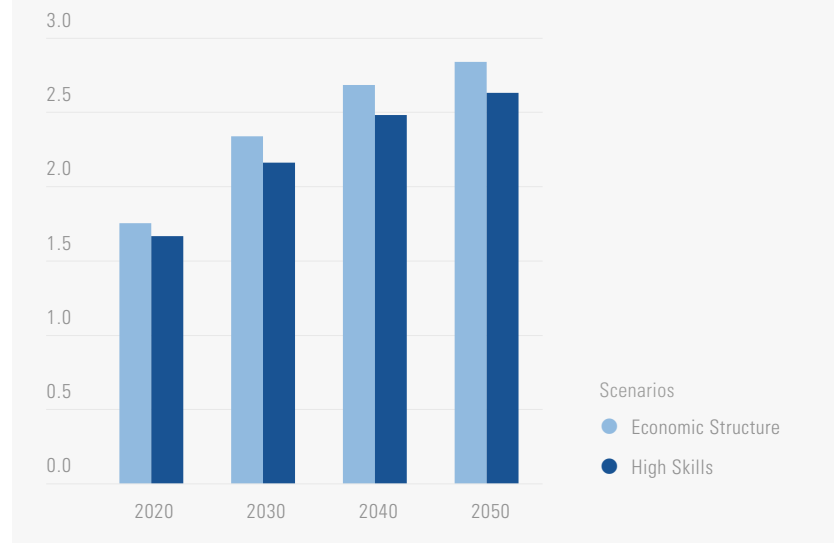
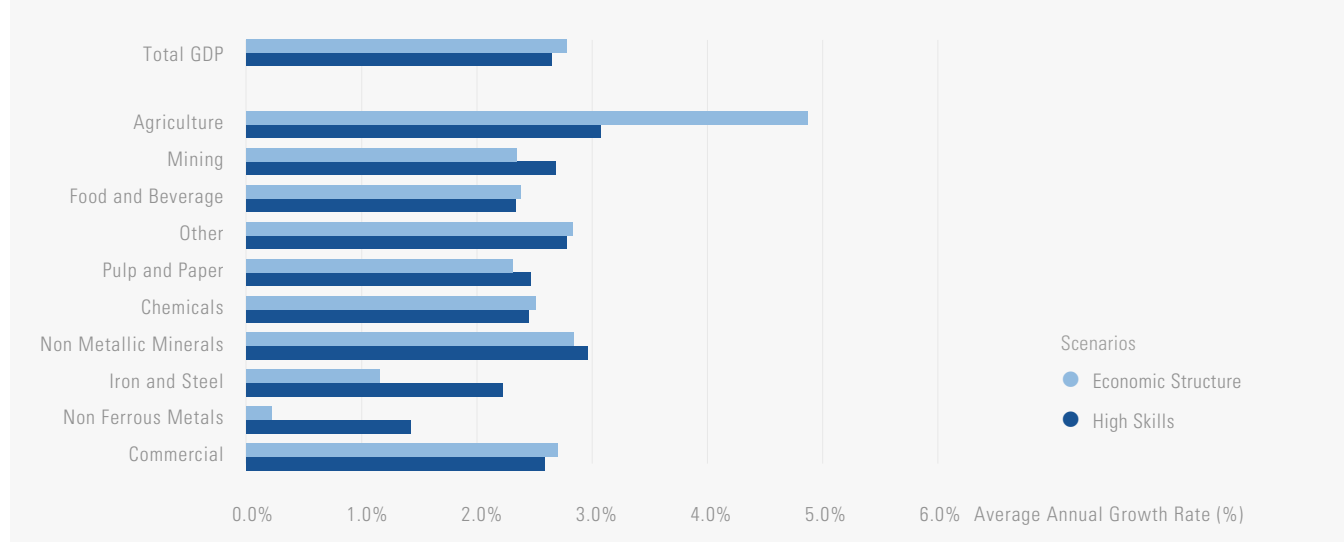


Figure 10. Average annual growth rate from 2010 to 2050 for total GDP and for key sectors



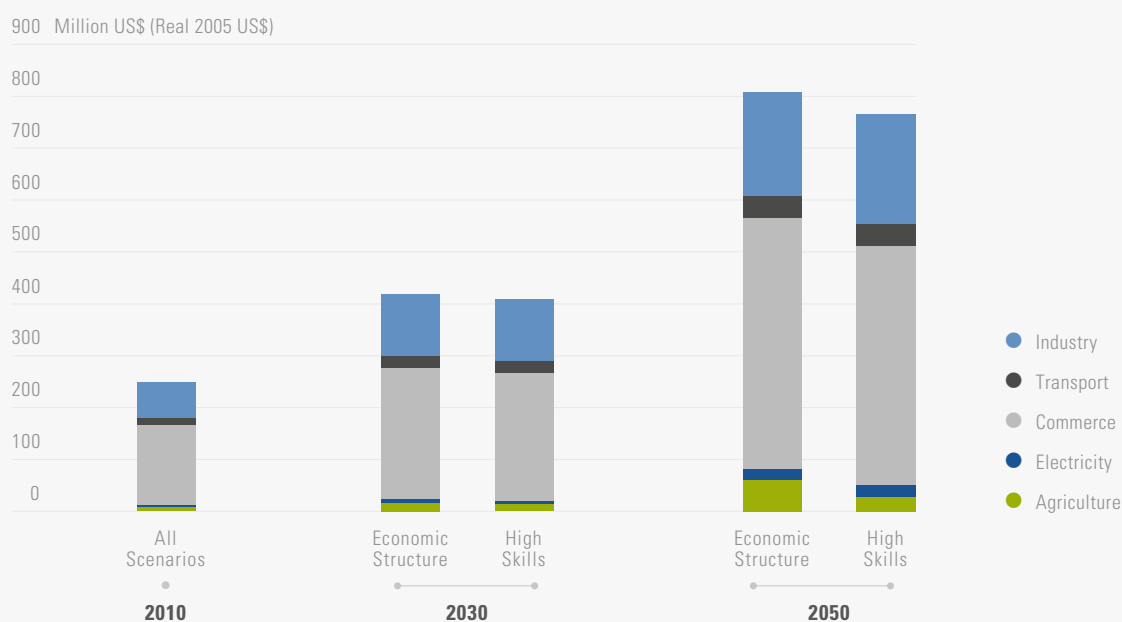
²² Currencies are presented in real 2005 US\$ converted using an exchange rate of R8.2 to US\$1.

and as such it cannot be prescribed at a certain level to match the given policy projections of the NDP or NGP. This is an advantage as no *a priori* required growth rate has to be assumed, and given South Africa's history of jobless growth (Banerjee *et al.*, 2008; Casale *et al.*, 2004), it is important to not place undue weight on annual GDP growth as a metric of development itself. The total GDP growth in both scenarios is consistent with recent projections for short-term growth from the South African National Treasury, which projects South Africa to grow at ~2% for 2015 with a gradual improvement to 3% through to 2017 (Budget Review, 2015). The Economic Structure Scenario has higher overall GDP, which is partially driven by the increased openness to trade allowing exports in the targeted sectors (i.e., agriculture, glass, etc.) to increase as well as spurring demand in the economy. Coal exports remain the same in both scenarios until ~2035, when high-grade coal exports flat-

ten out to 140 000 kt in the Economic Structure scenario, but increase to 161 000 kt in the High Skills scenario due to increases in growth in the coal sector, related to the overall increased industrial growth. In the High Skills Scenario, the increase in high skilled labour without exogenous structural changes to the economy results in lower overall GDP growth. Interestingly, this suggests that a focus on increasing the supply of skilled labour may lead to less favourable economic growth, as compared to changing the structure of the economy.

The sectoral growth rates differ between the two scenarios more than total GDP growth differs (Figure 10). The Economic Structure Scenario results in agriculture dominating sectoral growth at an annual average rate of 4.9%, with the next highest sector, non-metallic minerals, at 2.8%. The high growth rate in the agricultural sector is in contrast to the low growth in the iron and steel and non-ferrous metals sectors (1.2%

Figure 11. Value-added to GDP for major sectors in 2010, 2030 and 2050

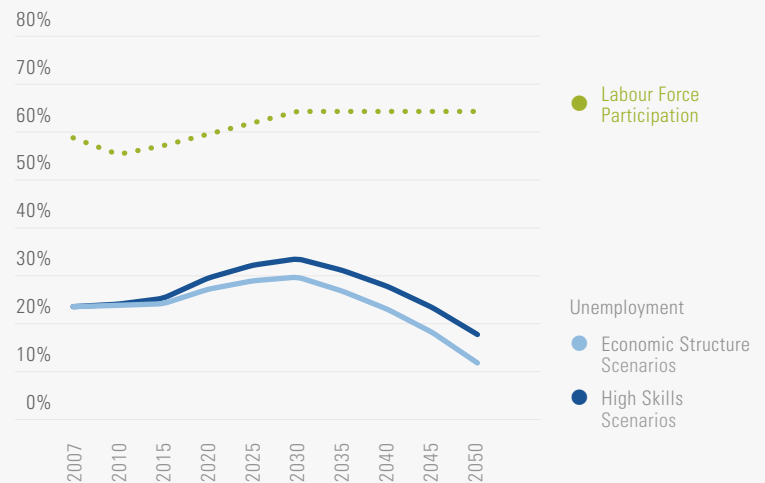


and 0.2%, respectively). The agricultural sector again has the highest growth rate in the High Skills Scenario (3.1%), but growth is much more evenly distributed in this scenario with non-metallic minerals at 3%, and the other industries and mining sector at just under 3%. Iron and steel and non-ferrous metals have significantly higher growth rates in the High Skills Scenario (2.2% and 1.4%, respectively) than in the Economic Structure Scenario. These differences are to be expected as the Economic Structure Scenario absorbs a large amount of unskilled labour into the economy, i.e., primarily into agriculture, while the High Skills Scenario utilizes the high skilled labour primarily in industry. However, overall value-added to GDP is still quite low for the agricultural sector (Figure 11), even in the Economic Structure Scenario. This suggests that changes to a relatively small sector (in terms of overall value-added to GDP), which do not lead to dramatic changes in the overall structure of the economy, can impact both employment and GHG emissions.

Both the structural shifts in the economy induced by growing low-carbon and high labour absorbing sectors, and the injection of high skilled labour, result in an increased uptake of labour into the economy by 2050, though to differing degrees (Figure 12).

In both scenarios, the unemployment rate increases until it peaks in 2030 at 30-34%, and then declines rapidly from 2030 through to 2050. This initial increase in unemployment is driven by the youth wage bulge joining the labour force (labour participation rate; Figure 12), and there are not enough new jobs to support the increase in the size of the working population. In both scenarios, the savings rate of the economy is initially 20% and exogenously starts to increase in 2015 until it reaches 25% in 2030. This can have a temporary and negative effect on consumption. Once the savings matures, it has a positive impact on unemployment and con-

Figure 12. Labour force participation rate over time and unemployment rate over time as calculated from the quantity of labour demanded in the e-SAGE CGE model



tributes to decreasing the unemployment rate.

Interestingly, though the pattern is similar for both scenarios, the Economic Structure Scenario ultimately results in a lower unemployment rate in 2050 than the High Skills Scenario (12% and 18%, respectively). The injection of high skills into the labour market in the High Skills Scenario does not happen immediately, which may contribute to the higher unemployment rate in 2050 as compared to the Economic Structure Scenario, where changes to the targeted sectors happens early on in the model runs. It is possible that adjustment of immigration policy for high skilled labour would result in the addition of high skilled labour into the economy earlier, while the educational policies were being implemented, such that domestic high skilled labour could substitute for the foreign high skilled labour over time. This could potentially make the High Skills Scenario more favorable in terms of its impacts on unemployment and would have to be explored further; indeed, future work will focus on a combined scenario with changes in

economic structure and the addition of high skilled labour.

These results are dramatically different from the goals of the New Growth Path and the National Development Plan. The NGP plans to incentivize labour absorbing industries such as agriculture, light manufacturing and services and aims to reduce unemployment to 15% by 2020. The NDP is even more aggressive with the goal to reduce unemployment to 14% by 2020 and 6% by 2030. Though the scenarios outlined here do ultimately reduce unemployment below the current level, there is a short-term period of increased unemployment and the 2050 values do not bring South Africa within the averages of other middle-income countries (5-7%; [Figure 4](#)). The Economic Structure Scenario results in the official unemployment rate being halved, from 25 to 12%, while the High Skills Scenario reduces the official rate by a quarter. Taken on their own, these values suggest two very different futures for South Africa in terms of social stability and basic security.

In 2007, there were 5.7 million employed unskilled labourers, and this category is largely where employment is gained. Through to 2050, the number of labourers employed in the unskilled category increases by 170% in the Economic Structure Scenario, but only 125% in the High Skills Scenario. In contrast, employment in semi-skilled labour increases by 29 and 46%, respectively, and employment in skilled labour increases by 24 and 37%, respectively in the two scenarios. The High Skills Scenario uptakes slightly more skilled and semi-skilled labour, but significantly less unskilled labour.

Unemployment is a key development indicator; however, if the unemployment rate falls

to zero by paying everyone a wage well below the poverty line, this could not be considered a successful development outcome. The Economic Structure Scenario does lead to slightly higher average wages in all income groups as compared to the High Skills Scenario. In the unskilled category, wages increase by 42% from 2007 to 2050 in the Economic Structure Scenario, whereas they increase by 37% in the High Skills Scenario. In both scenarios, there is a marked reduction in the percentage of the population classified as low income (< R19,200 per household per year; in 2007 Rands; [Figure 13](#)) and a distinct increase in the number of middle income (R19,200 to R76,800) and high income (>R76,800) households. These income brackets are chosen to represent key changes in end-use technology choice and energy consumption that occur with changes in income.²³

The percentage of households with access to electricity in each income group is determined exogenously, e.g., in 2010, 71% of the low income households, 83% of the middle income households, and 100% of the high income households are assumed to have access to electricity, and it increases with time. By 2050, 95% of low income households and 100% of all other households are exogenously assumed to have access to electricity. Therefore, the movement of households through income brackets determines the overall electrification rate and by 2050 only ~1% of households remain without access to electricity in both scenarios.

Both scenarios reduce the percentage of the population in the low income bracket from 49% in 2010 to ~18% in 2050, which is a marked improvement. In addition to high skilled labour being injected into the market, the High

²³ Five household groupings are used based on data from the Statistics South Africa's 2007 Community Survey, National Income Dynamics Study (NIDS), and All Media and Products Survey (AMPS) as discussed more fully in ERC, 2013 description of SATIM. The main choice of income bands was influenced by electrical appliance ownership.

Skills Scenario also allows for changes in the allocation of income from each labour factor to actively include more labour from those in the lower income deciles. This simulates an improvement in the education available to lower income households, and an increase in the ability of members of low income households to enter the job market. As a result, though the High Skills Scenario has a higher unemployment rate than the Economic Structure Scenario, there are still movements from lower to middle and high income brackets.

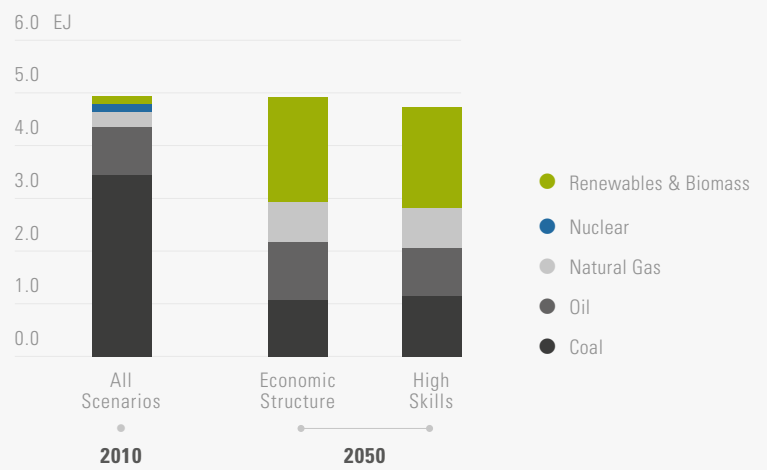
4.2 Energy and Economy

The composition of total primary energy supplied changes dramatically from 2010 to 2050 in both scenarios (Figure 14). The slightly higher total primary energy supply in 2050 in the Economic Structure Scenario is driven by the slightly higher GDP growth rate, economic structure, and energy efficiency changes over time.

In both scenarios decarbonization occurs through increased supply and demand technology effi-

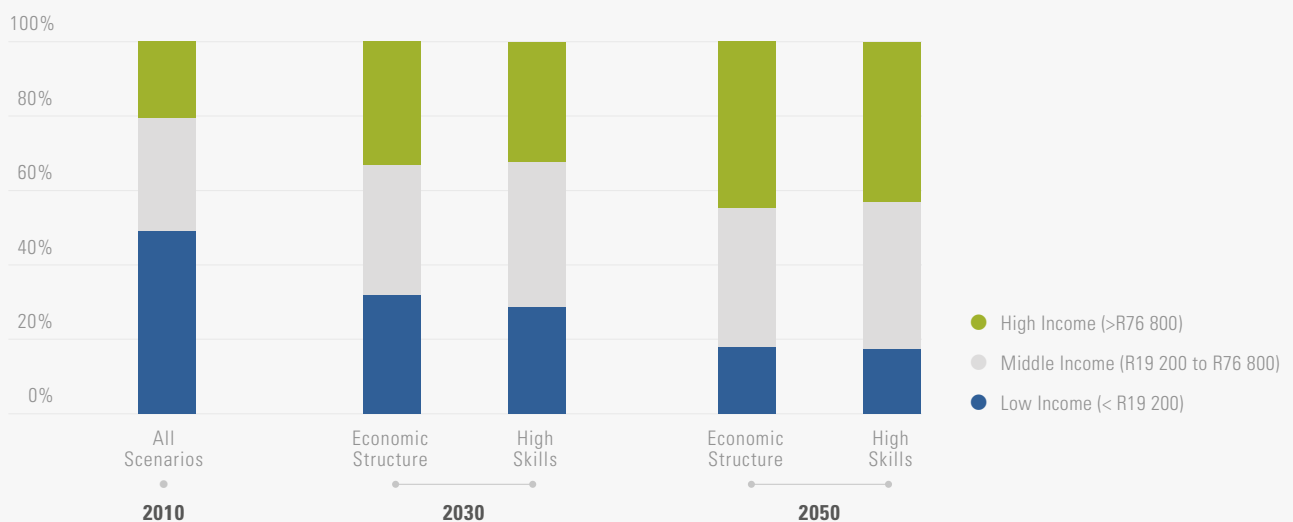
ciencies, end-use fuel switching, and increasing the share of renewables in electricity production with dramatic decreases in electricity generation from coal, very large increases in renewable energy and some penetration of natural gas. This is in

Figure 14. Primary energy in 2010 and in 2050



The renewables that contribute to the "Renewables & Biomass" category include solar PV, solar CSP and wind.

Figure 13. The percentage of the population in the low, middle and high income groups as defined by SATIM



line with the three pillars of decarbonization: the energy intensity of GDP, the emissions intensity of electricity, and subsequent increased use of electricity. Carbon, capture and storage (CCS) is not considered feasible for South Africa as the coal mines are located very far from potential storage

sites, and the current costs, as well as forecasted costs, are incredibly high, much greater even than nuclear costs (> US\$ 8,000/kW).

Despite the stable total primary energy supply in both scenarios, final energy increases significantly from 2010 to 2050 in both scenarios, with a slightly higher increase in the Economic Structure Scenario than in the High Skills Scenario, again partially driven by the higher GDP growth in Scenario 1 (Figure 15).

It is important to note that while the total amount of electricity use increases over time, the sources of electricity are dramatically different from 2010 to 2050, which is discussed in more detail in Section 4.3. There are similar increases in direct use of coal and gas from 2010 to 2050 in both scenarios. Liquid fuel use increases over time in the Economic Structure Scenario and decreases over time in the High Skills Scenario due to changes in agricultural consumption, though the share of agriculture in liquid fuels demand is modest compared to the transport sector. Sectoral changes will be discussed in more detail below.

Compared to 2010 energy emissions (398 Mt CO₂-eq), CO₂-eq emissions in 2050 decrease by 39% in Scenario 1 (to 241 Mt CO₂-eq) and Scenario 2 (to 242 Mt CO₂-eq) (Figure 16, Figure 17, Figure 18). This is at the low end of the official South Africa peak, plateau, and decline policy (National Climate Change Response White Paper, 2011), which in 2050 has a range of 212 to 428 Mt CO₂-eq for total GHG emissions, whereas here we present energy-only GHG emissions.

With the application of the cumulative energy emissions constraint, energy related CO₂-eq emissions do indeed follow a trajectory similar to peak, plateau and decline, peaking in 2030 at 449 Mt CO₂-eq before steadily declining until 2050 (Figure 17, Figure 18). It is important to note that all electricity related emissions are included in the “Electricity” sector and therefore emissions for the other sectors are non-electricity CO₂-eq emissions.

Figure 15. Final energy by fuel in 2010 and in 2050

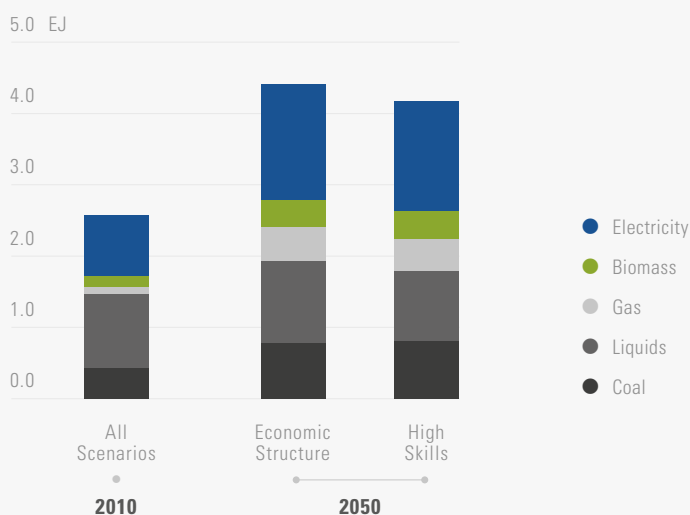
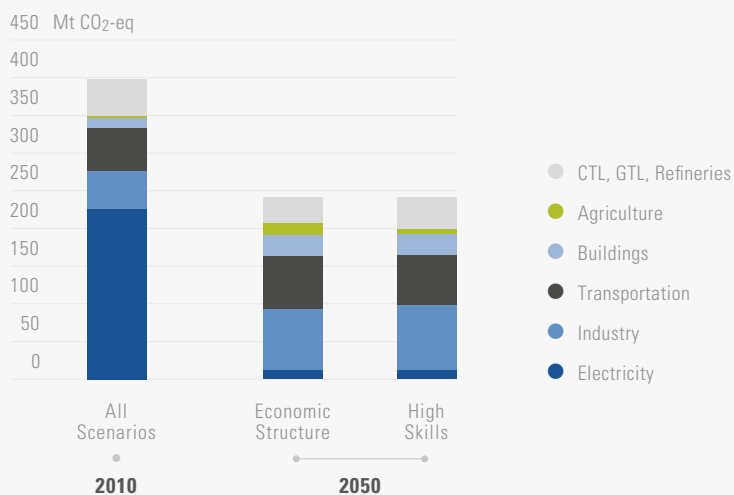


Figure 16. Energy Related CO₂-eq emissions in 2010 and 2050

The “Buildings” category includes residential and commercial emissions.



The decline in emissions results primarily from decarbonization of electricity and reduced emissions in the liquid fuel supply. The decarbonization of electricity allows for other sectors to switch towards using electricity as a low-carbon energy source. Overall, the main drivers of energy demand grow over time leading to an increase in final energy consumption. However, due to decarbonization of the electricity supply, efficiency gains and fuel switching, the overall energy intensity of the economy decreases significantly (Figure 19). From 2010 to 2050, GDP increases more than 200% and population increases 21% (Table 1), yet the energy intensity of the economy as measured by final energy (indicative of sectoral energy consumption) decreases by 40% in both scenarios and the energy intensity of the economy as measured by primary energy (indicative of the efficiency of the whole energy system including the production, transformation and end-use) decreases by 68%.

There are key components that drive decarbonization over time (Figure 20). The overall energy

Figure 19. Energy intensity of GDP in terms of final energy and primary energy

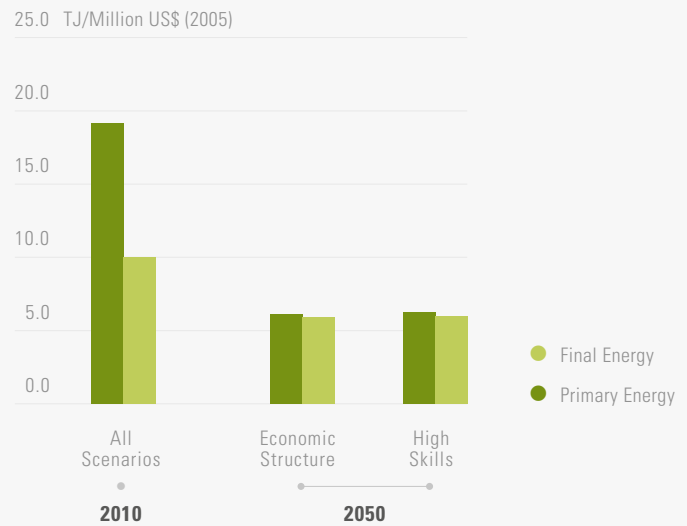


Figure 17 & 18. Energy related CO₂-eq emissions by sector

The "buildings" category includes residential and commercial emissions

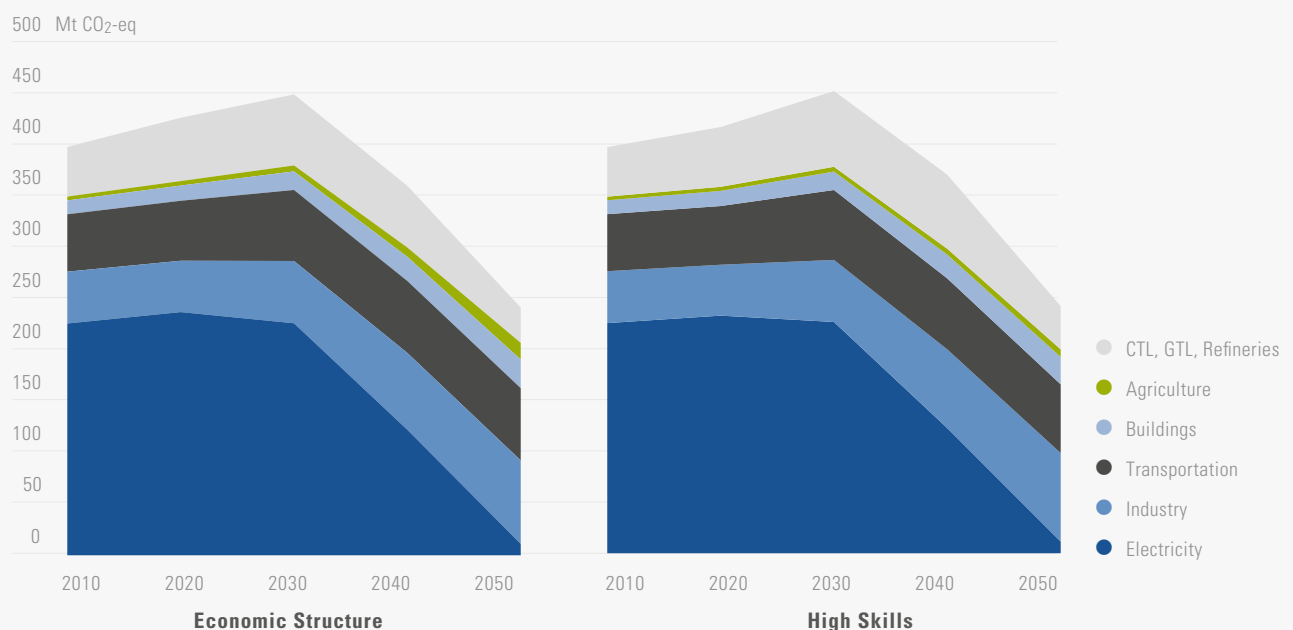
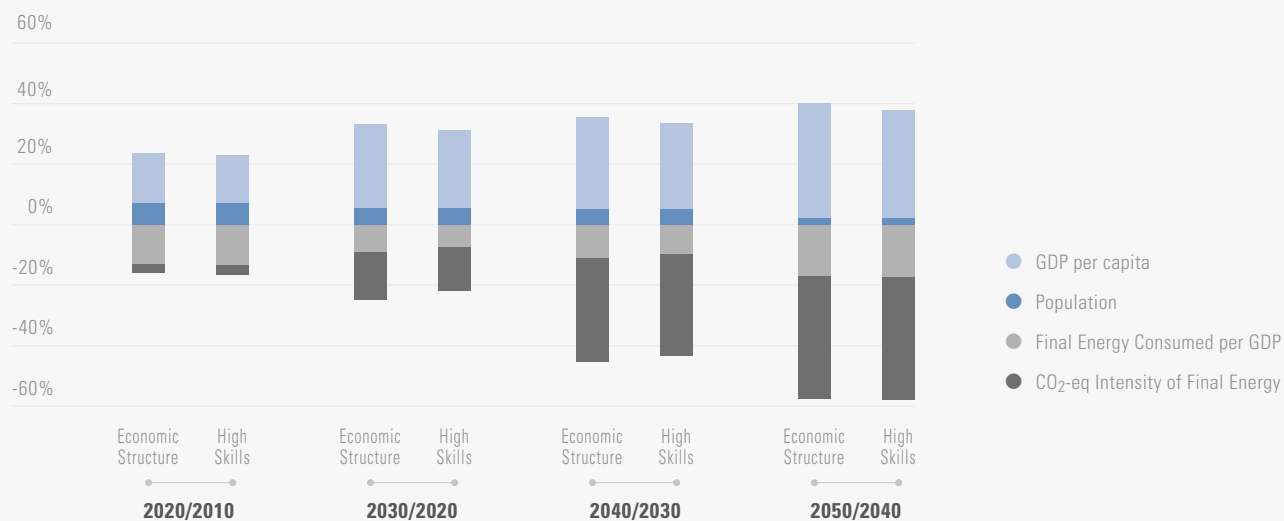


Figure 20. Energy related CO₂-eq emissions drivers from 2010 to 2050 expressed as the ten year variation rate of the drivers

emissions constraint of 14 Gt CO₂-eq is achieved while population, GDP per capita, and total energy consumption grow steadily over time (Figure 20). The large transition to negative growth in energy related CO₂-eq emissions occurs in the 2030

to 2040 time frame when construction of solar thermal, solar PV, and wind capacity ramps up in both scenarios to replace retiring coal fired power stations. Total energy GHG emissions per capita decrease from the currently very high value of 7.7 to 3.9 tons per capita between 2010 and 2050 (t/cap; Table 1), a value more in line with the current global average (5.8 t/cap), but still well above the order of magnitude necessary to achieve a 2°C world, around 1.5 t/cap (UNFCCC, 2010).

Figure 21. The electricity emissions intensity

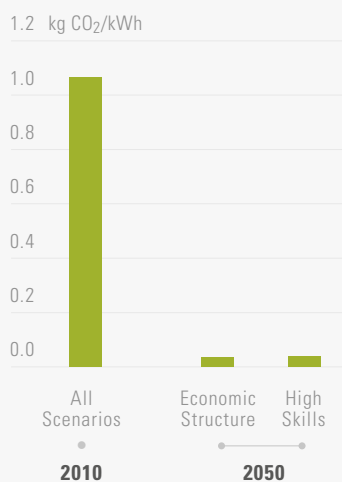
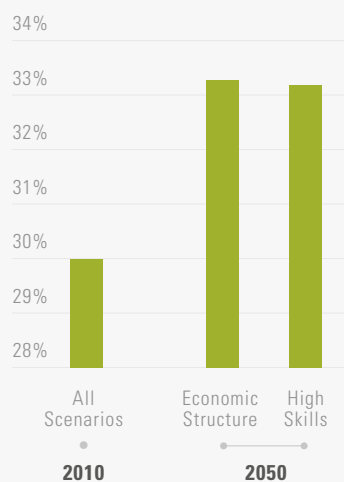


Figure 22. Electricity consumption as a percentage of final energy consumption



4.3 Electricity Sector

The majority of the GHG emissions reductions from 2010 to 2050 are achieved by the decarbonization of the electricity sector (Figure 21), followed by a switch to low-carbon electricity from higher-emissions fuels (Figure 22). There is also initially an increased use of electricity in the residential sector as people shift into higher income brackets, although both the quantity of electricity consumed and emissions are offset over time by efficiency improvements.

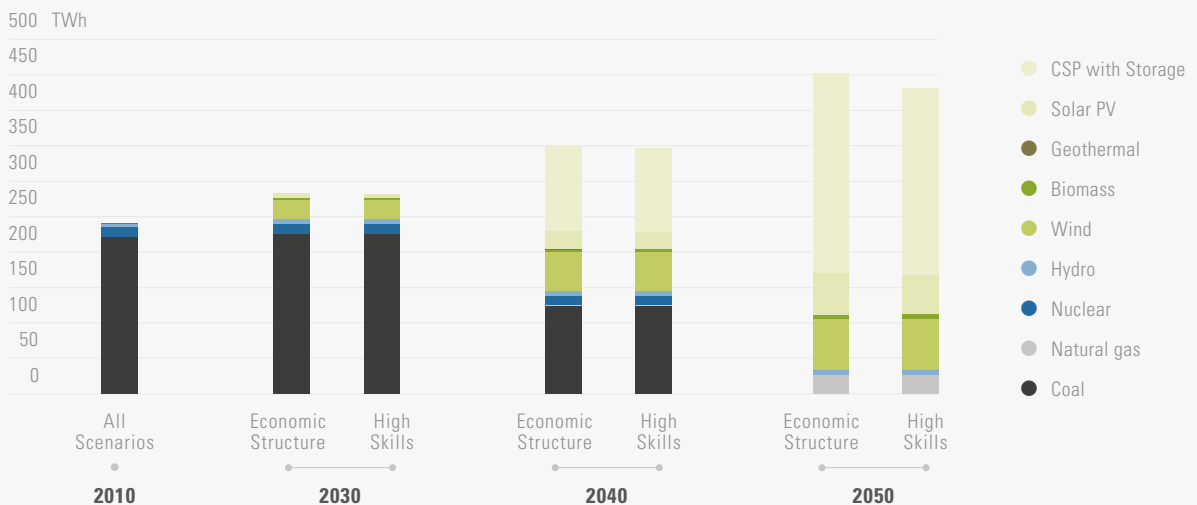
There are slight differences in electricity demand, electricity generated, and the resulting

supply mix between the Economic Structure and High Skills Scenarios. In the Economic Structure Scenario, electricity generation increases from 240 TWh in 2010 to 452 TWh in 2050, while in the High Skills Scenario electricity generation only increases to 431 TWh in 2050 (Figure 23). Overall, the total amount of electricity demanded is lower than expectations from the South African Integrated Resource Plan Update from 2010 (IRP Update 2010, 2013), largely due to the differences in GDP growth, which was assumed to be 5.4% in the IRP Update compared to the 2.6/2.8% presented here. In the Economic Structure Scenario, the agricultural sector consumes more than twice as much electricity as it does in the High Skills Scenario, whereas the industrial sector consumes approximately 10% more electricity in High Skills than in Economic Structure. The electricity sector undergoes almost complete decarbonization, with the generation emissions factor decreasing from 1,065 to 35 g/kWh from 2010 to 2050 in Scenario 1 and to 38 g/kWh in Scenario 2 (Figure 21). This is primarily achieved

through the end-of-life retirement of coal-fired power stations, including the two plants currently under construction, Medupi and Kusile. From 2010 to 2040, coal generation decreases by 44%, but then is completely eliminated by 2050 (Table 1 and Figure 23). There is no new investment in nuclear in either scenario, therefore when the Koeberg nuclear power plant retires in 2044, nuclear no longer contributes to electricity generation. Small amounts of gas contribute to the final generation mix, but gas does not become a significant electricity source as CSP is cheaper than LNG, and though gas is less CO₂ intensive than coal, it does produce GHG emissions. South Africa has a potentially large shale gas resource (Econometrix Report, 2012), which if developed may lead to a very different future energy mix. However, as the resource is still technically unproven, shale gas is not considered as part of this study and is beyond the scope of this report. Solar PV and wind start to contribute to electricity generation by 2020 with wind increasing significantly by 2030, while solar CSP does not make a large contribution until 2040. The differences between the two scenarios

Figure 23. The total amount of electricity produced over time

Carbon, capture and storage (CCS) is not a component of the South African decarbonization strategies.



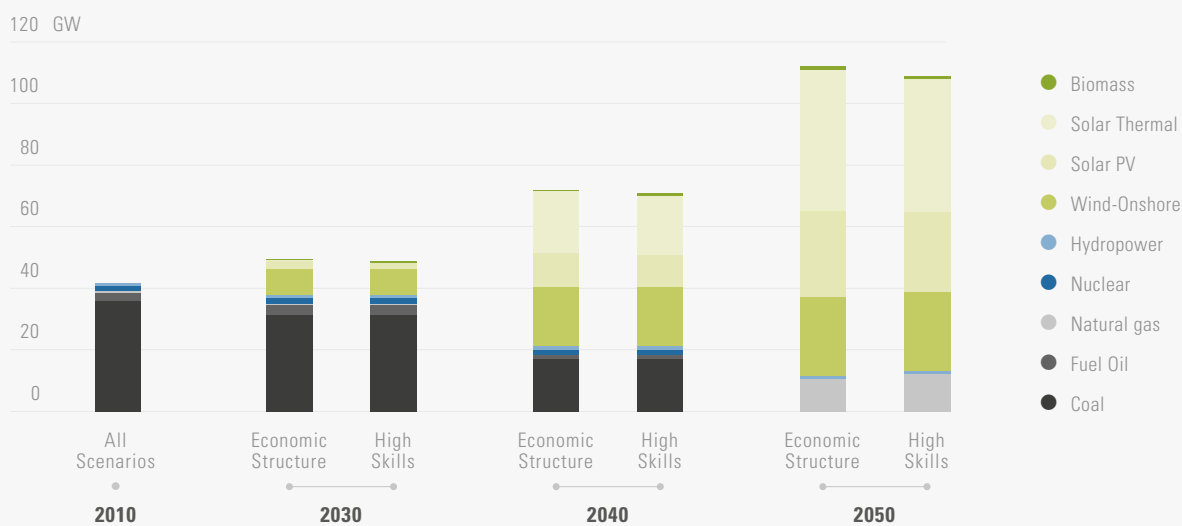
are minor, especially as compared to the dramatic changes that happen over time.

The carbon constraint leads to an almost complete transformation of the supply-side generation technology mix. By 2050, total capacity increases 2.7 times, while the contribution of coal-fired power decreases to zero (Figure 24). Non-fossil fuel technologies account for 89% of generation capacity by 2050 with solar PV and CSP with storage dominating at 63% of total capacity, and wind accounting for another 23%.

In both scenarios, there is no new addition of nuclear capacity, which suggests that given downward revisions in demand projections, there is not a pressing need to add nuclear capacity by 2030; this is consistent with the IRP 2010 update and the new power plan (IRP Update 2010, 2013; NPP, 2013). The wide-spread use of solar PV on commercial and residential properties, as well as the additional CSP capacity are plausible given South

Africa's vast solar radiation resources (Fluri *et al.*, 2009 and references therein) and the successful commercial contracting of a number of CSP plants in the 50-100 MW range.²⁴ However, it is important to note that the cost tradeoffs between wind, solar, and nuclear technologies are small. This particular technology mix could be exchanged for one with more wind or nuclear, without changing the fundamental result, which is decarbonization of the electricity supply mix in a manner that does not hamper economic growth as investment costs are of a similar magnitude. We present one such option above, which relies heavily on solar PV and CSP, but this is not a unique solution. The annual investment costs for the electricity sector (Figure 25) are consistent with the capacity changes over time (Figure 24). From 2025 to 2030, on-shore wind and solar PV are added to the supply mix leading to an increase in investment costs. Then from 2030 on through to 2045, large amounts of solar PV and solar CSP

Figure 24. Total electricity generating capacity over time



²⁴ There is currently one CSP plant in production in South Africa, the Kaxu Solar One 100 MW plant, with 6 additional plants under development or construction, and development times currently 3 to 4 years. Thus, the technology and utility scale deployment at commercial rates are proven in South Africa.

with storage are installed, leading to consistently high investment costs over that time period.

4.4 Liquid Fuels

The demand for liquid fuels increases over time in the Economic Structure Scenario, while in the High Skills Scenario, it increases initially and then ultimately decreases for reasons elaborated below (Figure 26). Gas-to-liquids (GTL) is completely phased out by 2030 in both scenarios. Coal-to-liquids (CTL) declines over time but is still present in 2050. As CTL is decreased, the emissions intensity of liquids undergoes a substantial decline.

Overall, liquid fuels production emissions intensity is reduced by the reduction in CTL and GTL by 2050 in both scenarios (Figure 26). In the High Skills Scenario, the demand for liquid fuels decreases as GTL is phased out and CTL is reduced, though in the Economic Structure Scenario de-

mand continues to increase over time. Agricultural liquid fuels demand is 55% higher and transport demand is 5% higher in the Economic Structure

Figure 25. Annual investment cost of the electricity sector in billions of US\$

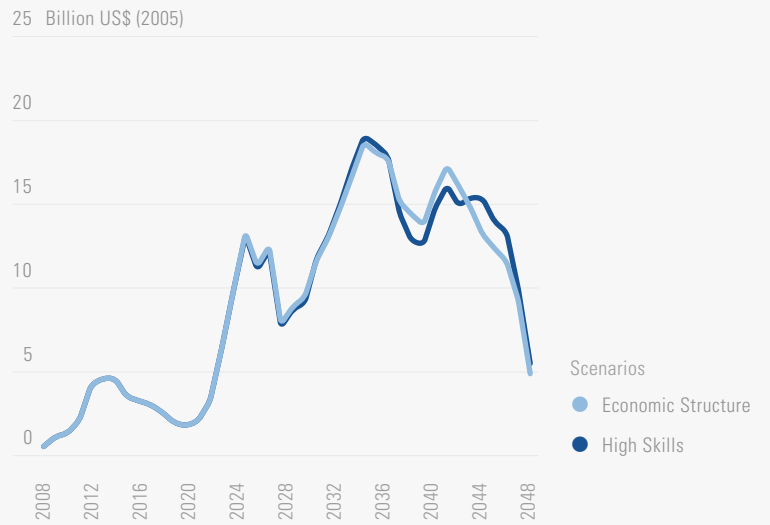
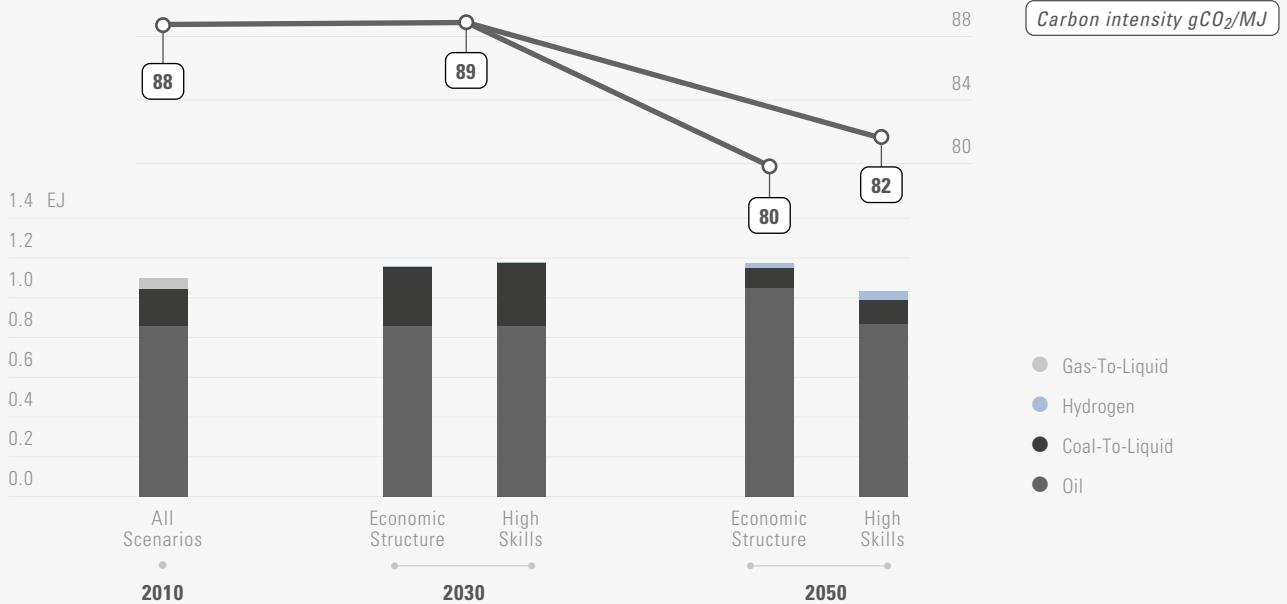


Figure 26. Emissions intensity of the liquids sector and liquids production over time by process.



Scenario as compared to the High Skills Scenario. This is offset by the 18% higher demand in industry in the High Skills Scenario, particularly in the iron and steel and mining subsectors. This highlights the implications of differing socio-economic policies on the future of key industries under a carbon constraint.

4.5 Industry

Total industry value-added increases from 2010 to 2050 in both scenarios, though in the Economic Structure Scenario it increases at an annual average rate just under total GDP (2.7% industry vs. 2.8% total) due to the increased importance of the agriculture sector, whereas in the High Skills Scenario it increases at an annual average rate slightly greater than total GDP (2.9% industry vs. 2.6% total) due to the increased supply of skilled labour to industry (Figure 10). As a result, total industry value add to GDP is

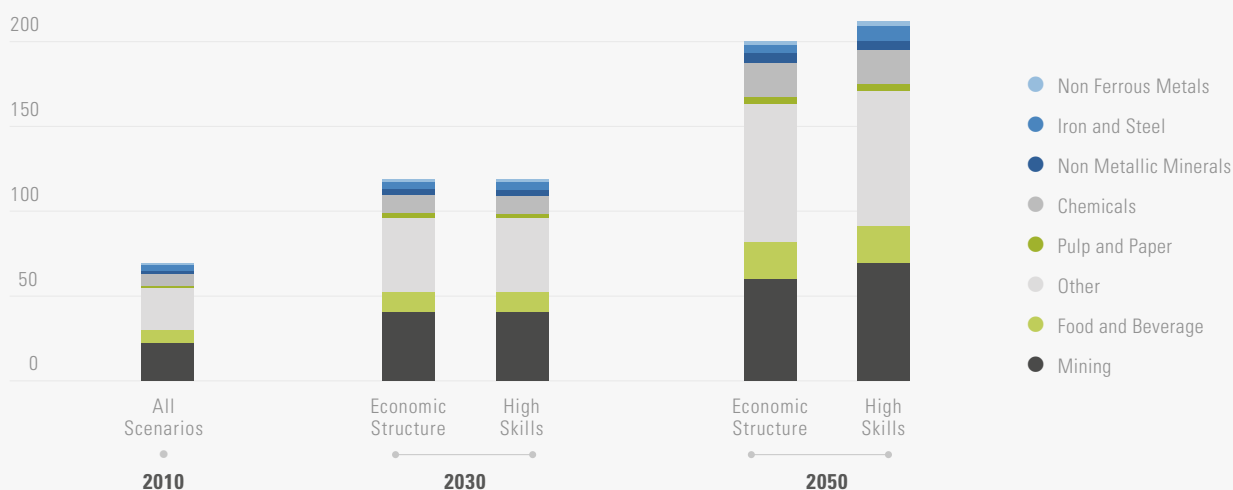
higher by 2050 in the High Skills Scenario than in the Economic Structure Scenario (Figures 27, 28, 29), as evidenced by the differing average annual growth rates of industrial subsectors (Figure 10). Within the industry sector, different subsectors respond differently in the two scenarios. Total value-added to GDP is higher in the High Skills Scenario with the injection of high skilled labour into the market. This is primarily driven by increased growth in iron and steel and non-ferrous metals as compared to the Economic Structure Scenario. The “Other” sector includes construction, agro-processing, car manufacturing, machinery, and uncategorized industrial subsectors.

As value-added to GDP and final energy consumption increase, total GHG emissions increase, but only until 2030. At that time, value-added to GDP and final energy continue to increase, but electricity decarbonization results in a decrease in total GHG emissions from 2030 to 2050. Efficiency gains are occurring throughout the

Figure 27. Industry value add to GDP by industrial subsector

The “Other” sector includes construction, agro-processing, car manufacturing, machinery, and uncategorized industrial subsectors.

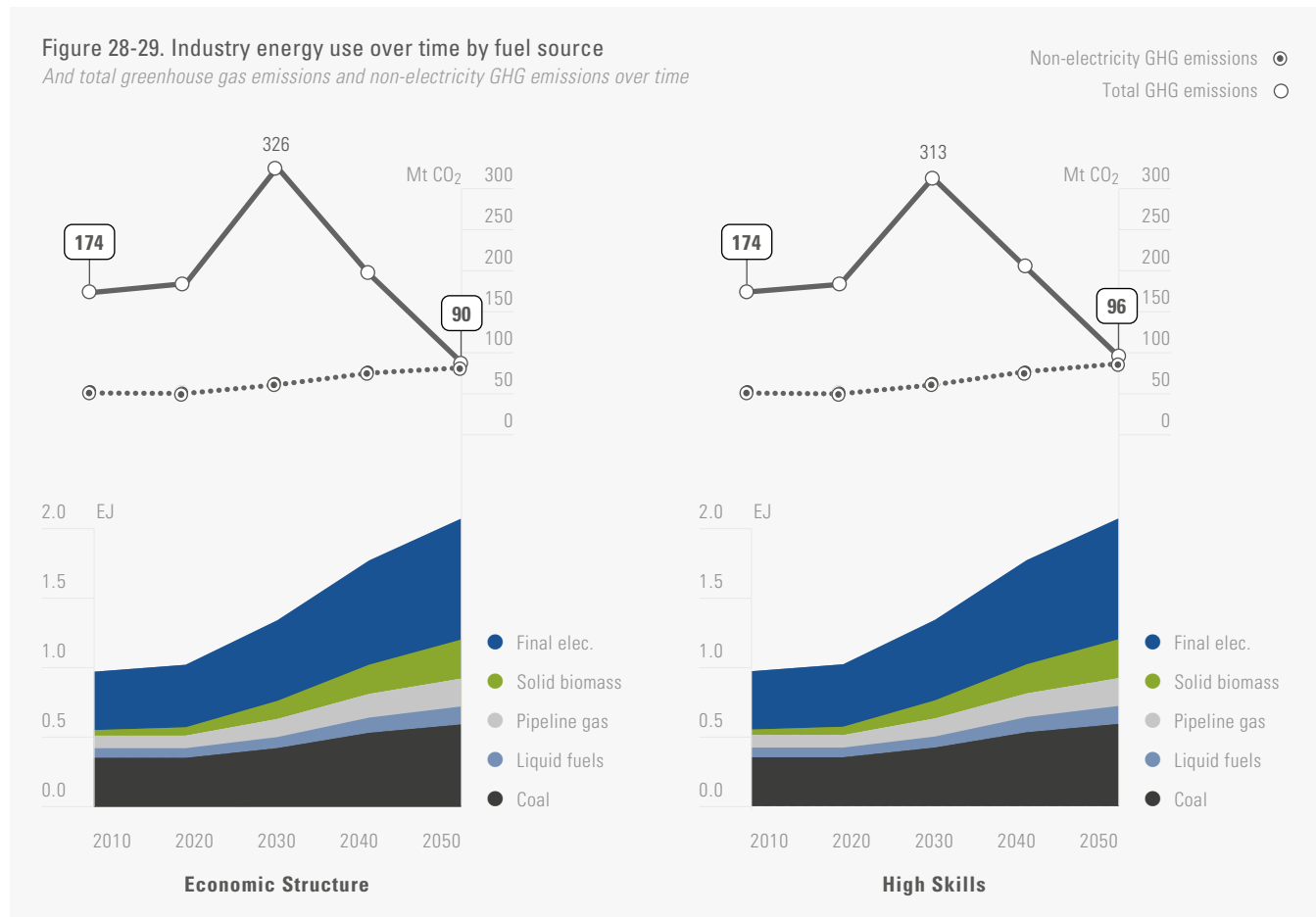
250 Million US\$ (Real 2005)



time-frame, such that as final energy increases over time non-electricity GHG emissions rise at a much lower rate (Figures 28, 29), and indeed eventually decline.

Interestingly, GHG emissions peak at a lower value in 2030 in the High Skills Scenario (314 Mt CO₂-eq) than in the Economic Structure Scenario (326 Mt CO₂-eq), but then decrease less rapidly ending up at 96 Mt CO₂-eq in 2050 as compared to 89 Mt CO₂-eq in the Economic Structure Scenario (Figures 28, 29). This is due to the emissions intensity of electricity, which is slightly lower in the High Skills than in the Economic Structure Scenario in 2030, though by 2050 the electricity emissions intensity of the Economic Structure Scenario is lower than

the High Skills Scenario. The electricity sector emissions are similar in both scenarios, but the total electricity generated is higher in 2030 in the High Skills Scenario. Decreases in industry GHG emissions are achieved by a combination of fuel switching from coal to gas (or electricity), efficiency improvements, and increased use of low-carbon electricity. The relative contribution of efficiency gains and fuel switching to electricity is evident by the differences in the total GHG emissions over time and the non-electricity GHG emissions over time (Figures 28, 29). Total GHG emissions decline due to increased use of electricity, whereas non-electricity emissions remain steady throughout the period due to energy efficiency gains.



4.6 Agriculture

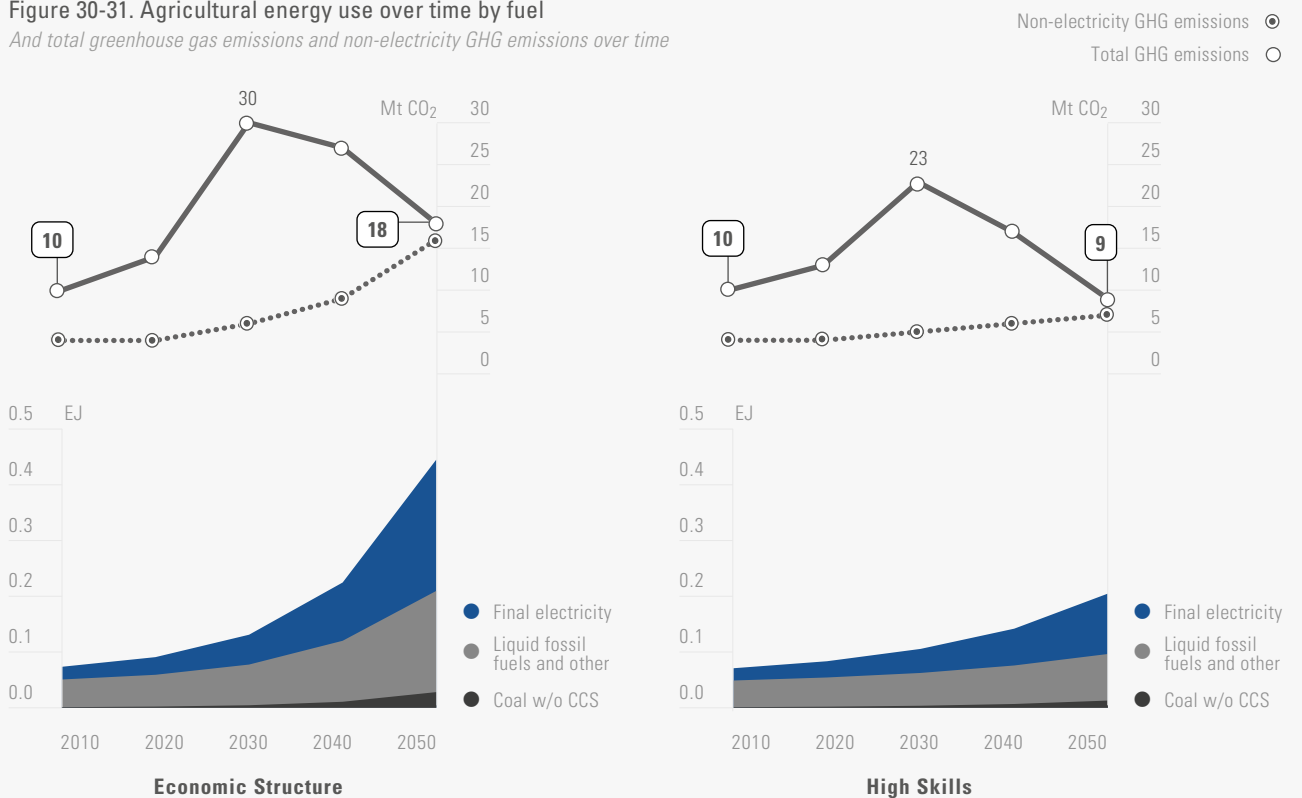
In the Economic Structure Scenario, the agricultural sector absorbs unskilled labour and exports agricultural products. As a result, the percentage of value-added to total GDP in 2050 is 7.5% in the Economic Structure Scenario vs. 3.7% in the High Skills Scenario (Figure 11). This leads to a more than doubling of energy consumption, along with a switch to increased electricity consumption. Non-electricity GHG emissions from the agricultural sector increase by 4.3 times from 2010 to 2050 in the Economic Structure Scenario, and 2.1 times in the High Skills Scenario (Figures 30, 31). Overall, agriculture is a minor contributor to total GHG emissions and energy consumption, but the large changes within agriculture do impact the electricity and liquid fuels production sectors significantly. It is important to note that

these increases in agricultural productivity are dependent on water availability, which is a scarce resource in South Africa, and therefore the type of agriculture would be an important component of policies designed to simulate the Economic Structure Scenario changes. The total agricultural GHG emissions would also be dependent on the type of agriculture pursued, livestock vs. crop focused farming, as well as farming practices, e.g., non-till farming and manure management (CDM in Agricultural Sector South Africa, 2008).

4.7 Residential and Commercial

Residential sector final energy increases over time as population increases (Figure 32). However, the rate of population is increasing faster than the rate of final energy consumption, highlighting the efficiency gains that are made. There is a

Figure 30-31. Agricultural energy use over time by fuel
And total greenhouse gas emissions and non-electricity GHG emissions over time



large uptake of solar water heaters and more efficient gas appliances. The use of gas is primarily for cooking, and not for heating homes. Biomass is used by both low- and middle-income groups for cooking, space heating, and water heating. As coal and fossil fuels are used less, and electricity

becomes decarbonized, the average emissions intensity of the residential sector decreases by 90% from 2010 to 2050 in both scenarios.

The commercial sector value-added to GDP increases significantly over time (Figure 11) as does final energy consumption (Figure 33). There is a

Figure 32. Residential energy use over time

The "solar thermal" category represents solar water heaters. Fossil fuels include lpg and kerosene.

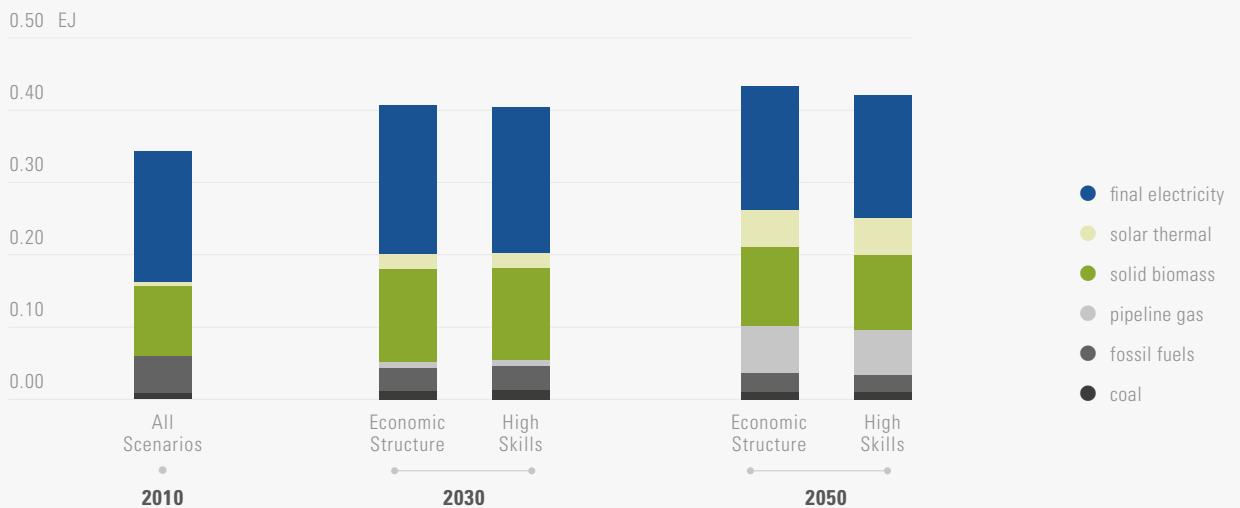
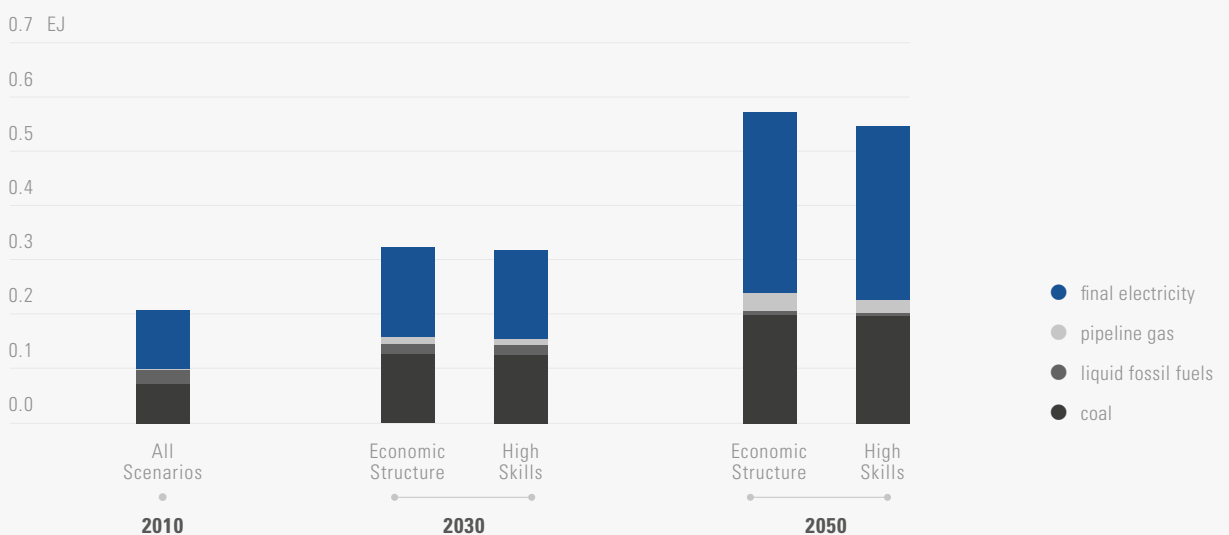


Figure 33. Commercial energy use over time



large switch to using electricity over time after the electricity sector decarbonizes. There are also exogenous increases in building efficiencies put into the model based on improved standards that are in the process of being implemented. Within the model, there are endogenous choices related to solar PV, heat pumps, and CHP that the commercial sector can implement to increase efficiency.

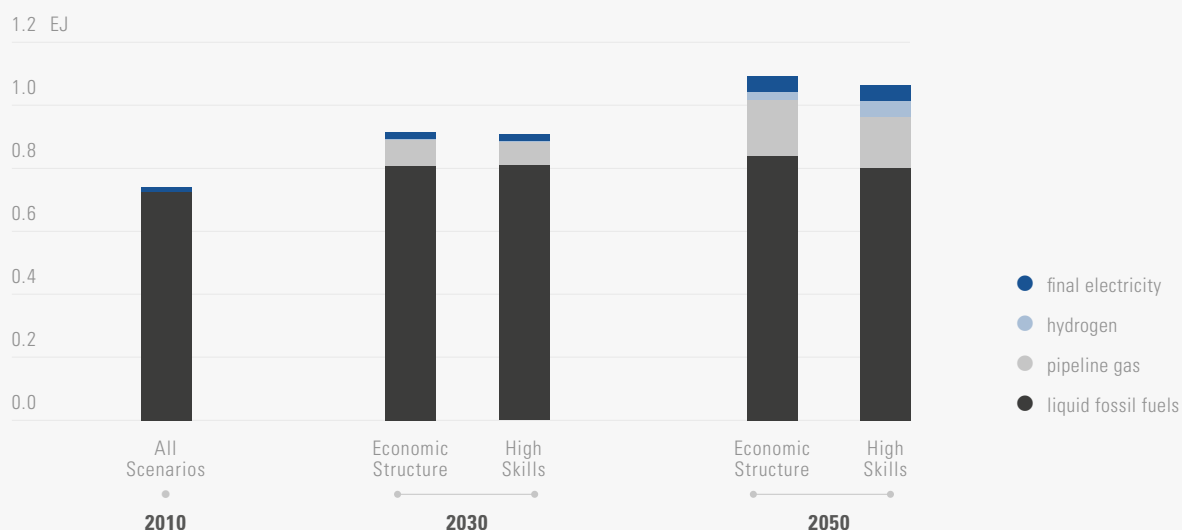
4.8 Passenger Transport

Total passenger kilometers traveled increase from 289 billion passenger kilometers (p-km) in 2010 to ~444 billion p-km in 2050, an overall increase of 54%. Car travel increases from 128 billion p-km to 272 billion p-km, while public travel only increases modestly from 158 billion p-km to 167 billion p-km. Both scenarios have a steady p-km traveled increase of 1% per year through to 2050. The p-km per capita increase from 5,615 to 7,126, an increase of 27%. The model endogenously decides how to utilize the different vehicles

available to meet transport demand. Total vehicle ownership increases from 5 million vehicles to 11.1 million vehicles in the Economic Structure Scenario and to 10.9 million vehicles in the High Skills Scenario. This reflects a significant increase in the access to private transportation (10.2 people per vehicle in 2010 to ~5.7 people per vehicle in 2050), an important development metric.

The efficiency gains are due to a combination of modal shift and vehicle efficiency improvements. For example, diesel and gasoline private vehicles improve from 6.9 liters per 100 km (l/100km) to 4.5 l/100 km and from 8.3 l/100 km to 5.4 l/100 km, respectively. Diesel minibus taxis also improve significantly from 11.5 to 7.4 l/100 km. The opportunities for modal shift to electric vehicles only occur after ~2030 when the electricity sector starts to decarbonize. Compressed natural gas (CNG) vehicles join the fleet after 2030 in both scenarios. Electric vehicle sales are similar in both scenarios, 42% of new vehicle sales and 15% of the vehicle fleet in 2050, and they start being sold after 2040.

Figure 34. Transport energy use over time



4.9 Freight Transport

Freight transport demand is driven by sectoral GDP growth and associated transport needs. Total freight increases from 273 billion ton-km in 2010 to 674 billion ton-km in 2050. The ratio of road to rail freight remains fairly constant at 54% to 46%. Final energy consumption increases 85% in the Economic Structure Scenario and 81% in the High Skills Scenario over that time period, and total GHG emissions increase 56% and 52% from 25 Mt CO₂-eq in 2010 to ~40 Mt CO₂-eq in 2050, respectively. In the model, it is assumed that the intensity of freight transport per unit of production increases by 1% per year over time. The rate of GHG emissions growth lags behind final energy consumption due to vehicle efficiency improvements. As a result of these efficiency improvements, freight emissions intensity decreases

by 15% from 2010 to 2050, however, it should be noted that there are opportunities for modal shifts from road to rail as deeper GHG emissions cuts are required.

The final energy consumption associated with total transport increases by 42% from 2010 to 2050 in the High Skills Scenario and by 46% in the Economic Structure Scenario (Figure 34). This slight differences between the scenarios is reflected in the fuel consumption. The Economic Structure Scenario has higher electricity and gas consumption than the High Skills Scenario, but the High Skills Scenario has much higher uptake of hydrogen and a larger decrease in liquid fossil fuels consumption. The impact on GHG emissions is negligible, and in both scenarios GHG emissions from passenger transport increase by ~6%, while passenger miles traveled per capita increases by 36% from 2010 to 2050.

5 Discussion

5.1 Climate Indicators

Energy GHG emissions follow a peak plateau and decline trajectory in both scenarios. The electricity system undergoes significant decarbonization in both scenarios, with wind, solar PV, and solar thermal dominating electricity generation by 2050, though as discussed above this is one representative technology mix of many. The similarities in electricity are interesting as there are structural differences between the two scenarios driven by differences in agriculture and industry. The absolute value of emissions in 2050 is within 1 Mt CO₂-eq between the two scenarios, but the distribution of emissions differs. The agricultural sector has higher emissions in the Economic Structure Scenario than in the High Skills Scenario, while the opposite is true for the liquid fuels sector. The model will allocate the implic-

it national carbon budget in the most efficient manner over time; hence both scenarios remain under the carbon constraint, but with differing temporal emissions pathways as well as differing impacts on sectors and the economy.

5.2 Development Indicators

The scenarios explored in this study assume that all efforts to decarbonize the economy are achieved at the same time as South Africa pursues development goals. Lower poverty and inequality are goals that cannot be sacrificed to lower emissions. The National Development Plan of South Africa outlines objectives, including reducing poverty and inequality with a key focus on education and employment. The two scenarios discussed in this work have been de-

signed to represent changes to employment and educational policies. A key result of this work is that improvements in development metrics can be achieved under a carbon constraint. Both scenarios resulted in the same overall GHG emissions reductions, and had similar reductions in the number of low income households, improvements in the distribution of income, and increases in the number of private vehicles owned. However, the Economic Structure Scenario had higher GDP growth as well as lower unemployment than the High Skills Scenario, rendering it a more attractive result. It is important to note though, that in the Economic Structure Scenario there was intensive growth in the agricultural sector and diminished growth in some industrial subsectors. In both scenarios, joblessness is still high by mid-century, which highlights the difficulties of South Africa's current development situation, even in the absence of mitigation efforts. This brings up serious questions with respect to water availability, international terms of trade, and what type of future South Africa desires. This work highlights that there are key interactions among economic, development, and climate policies that must be explored when attempting to achieve multiple climate and development goals.

5.3 Transformations of energy supply

The energy emissions constraint is achieved by rapid decarbonization of electricity supply from 2030 to 2050 and a shift away from emissions intensive GTL and CTL. This leaves opportunities for additional cuts via non-electricity emissions reductions. Solar CSP with storage and solar PV dominate electricity supply in both scenarios, representing 75% of electricity production and 66% of installed capacity by 2050. This is realistic for

South Africa given the strong solar resource, as well as recent data from solar installations that show capacity factors for solar PV plants at 27%, much higher than was originally expected. The addition of solar thermal and PV to the generation mix is partially driven by the technology learning curves applied over time, which simulate the reduction in renewable energy costs over time due to increased learning and economies of scale (Winkler *et al.*, 2009). Learning curves are impacted by the context of both local and global markets. The learning rates used in this modeling are actually more conservative than the South Africa specific learning curves used in the IRP (2010), suggesting that the increased uptake of solar is realistic in these scenarios. It also suggests that South Africa would benefit from increased research, uptake, and production of solar technologies globally as this would contribute significantly to local price reductions.

On-shore wind has seen increased uptake in South Africa over the past three years as a result of the Renewable Energy Independent Power Producer Programme. The actual capacity factor of new wind farms in South Africa is exceeding expectations and has been as high as 38% in some regions. The most optimistic capacity factor in the current SATIM model is 30%; therefore as new wind data continue to be acquired, the model will be updated to reflect these higher capacity factors. This will likely result in wind contributing even more to generation capacity over time and may slightly reduce the dominance of solar CSP and PV,²⁵ while also providing opportunities for the complete decarbonization of the electricity sector. This again highlights the multiple technologies available to achieve deep decarbonization.

Meeting development and climate goals requires changes in the minerals-energy complex,

²⁵ Unless the PV capacity factors also turn out to be higher than expected.

and provides unique opportunities for industrial investment and growth. In both scenarios, there are structural changes to industrial subsectors as well as the liquids production sector of the economy, though there are differences between the two scenarios. The value-added of industry to GDP grows significantly in both scenarios, with a shift towards agricultural growth under the Economic Structure Scenario, while the High Skills Scenario retains a greater share of economic output in industrial sub-sectors. Efficiency improvements and fuel switching lead to industrial GHG emissions decreases in both scenarios, while value-added increases. Within the industrial subsectors, there are distinct differences in terms of iron and steel and non-ferrous metals growth. The Economic Structure Scenario results in reduced growth in these sub-sectors due to the emphasis on absorbing unskilled labour in sectors with low GHG emissions, which shifts growth to the agricultural sector. Job growth in the agricultural sector has different impacts on society than job growth in industry. Agricultural jobs tend to be spread out across the country, which impacts urbanization and the growth of cities, as well as rural development, all areas for more in-depth research.

Gas- and coal-to-liquids processes (GTL and CTL, respectively) are reduced over time due to the presence of the carbon constraint. GTL is phased out by 2030, whereas CTL is reduced by 50% by 2050 in the Economic Structure Scenario and 39% in the High Skills Scenario. The demand for liquid fuels decreases over time in the High Skills Scenario, but rises over time in the Economic Structure Scenario. This is a fairly dramatic transition for the liquid fuels sector as a result of the need to meet development and climate imperatives.

Maintaining a feasible energy supply system to meet the growing needs of industrial, commercial, and residential sectors while meeting the energy emissions constraint requires significant

decarbonization in the electricity sector. Coal-fired electricity generation will not be replaced when it retires, and low-carbon technologies will have to be deployed on a large scale. The exact composition of this transition to a decarbonized electricity supply system will influence the associated grid expansion and changes in end use technology. The decarbonization of the electricity system encourages other sectors to increase reliance on electricity. This, and the increased mobility of a wealthier population, provide an opportunity for a large-scale switch to alternative transport fuels and the use of electric, hybrid and hydrogen vehicles.

The two scenarios presented here are two potential pathways to improve development metrics while meeting a carbon constraint. They are two of many options that must be evaluated within government and by stakeholders at all levels. Indeed, a third scenario with changes to both the economic structure and skills profile would be interesting to evaluate. The differing impacts on sectors between the two scenarios highlight the need for careful evaluation of linked development and climate policies. This type of transformative change has to be determined at a national level in-line with national development and growth priorities.

5.4 Implications for Global Climate Policy

South Africa may aspire to zero poverty and zero emissions in the long term, but is this possible? This study has examined the twin challenges of development and climate change, and finds that it is technically feasible for South Africa to meet a 14 Gt CO₂-eq constraint on energy emissions while improving on key development imperatives. Meeting the peak, plateau, and decline emissions trajectory requires major transformations in the energy system. The focus of this country report was to analyze the techno-eco-

economic pathways to meet development imperatives and decarbonization pathways. This study has focused on the long term, which is important for large investments and clear policy signals. However, there are rigidities in socio-economic systems, particularly in the short term, that need to be taken into account. The political economy paper, currently under development, will investigate the feasibility of modeled pathways in South Africa's political economy, and will explore why these technologically feasible scenarios for deep decarbonization might be blocked by countervailing societal forces or alternatively, how they are being translated into socially and politically acceptable solutions in South Africa. How much of the mitigation potential in these technologically feasible scenarios for deep decarbonization can be realized depends on economic, social and political factors. The investments required to decarbonize the electricity sector are presented, and at some stages are as high as 14% of total investment (Figure 25). However, the detailed and sector-specific investments required are not yet fully quantified, and the sources of finance required to make such investments affordable not examined here. This study could be expanded by the use of a more sophisticated financial model, where the financial flows and investment requirements could be fully disseminated. From a global perspective, there are certain investment flows from developed to developing countries, as well as flows among developing countries, required to support deep decarbonization in developing countries. In this case, investment includes financial support as well as technological support. The rapid decarbonization of electricity supply envisaged in this study would only be affordable if technology costs are significantly reduced. Learning rates are a function of global installed capacity, and costs need to be brought down in developed countries. South Africa faces a high opportunity cost of invest-

ment in mitigation, notably investment in the reduction of poverty and inequality through employment and education. This study suggests that unemployment can at best be halved by mid-century. There is a certain amount of cooperation and collaboration inherent in the decarbonization process that requires joint action from developing and developed countries. An important component of this cooperation lies in the realm of international trade, ensuring that global demand for all goods and services can be met, especially with respect to energy intensive goods.

The current study is based on important methodological innovations, notably linking the SATIM-E energy model to an economy-wide CGE model expanded for energy, eSAGE. Equally important is the innovation in representing changes in the economic structure, and explicitly addressing South Africa's top policy priority of employment in this context. This research will be extended through analysis of what modeled scenarios might be blocked or supported in South Africa's political economy. Much further research is needed to provide a strong evidence base for urgent action on development and climate in South Africa.

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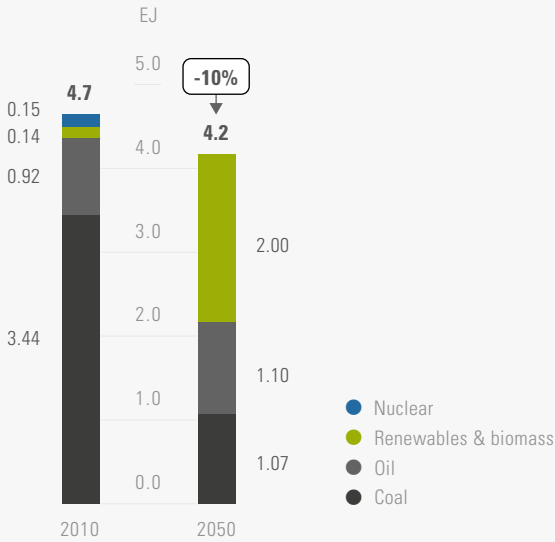
Standardized DDPP graphics for South Africa scenarios

ZAF – Economic Structure

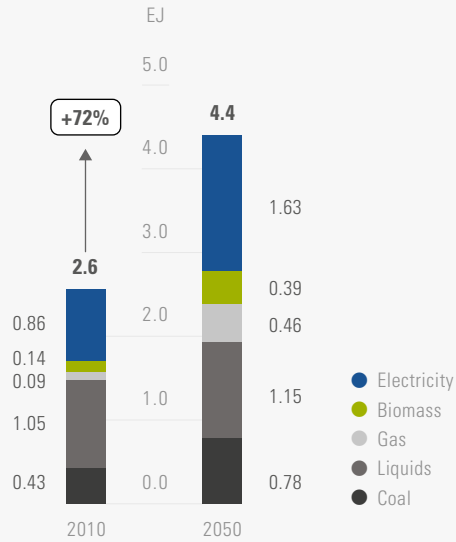
ZAF – High Skills

ZAF – Economic Structure

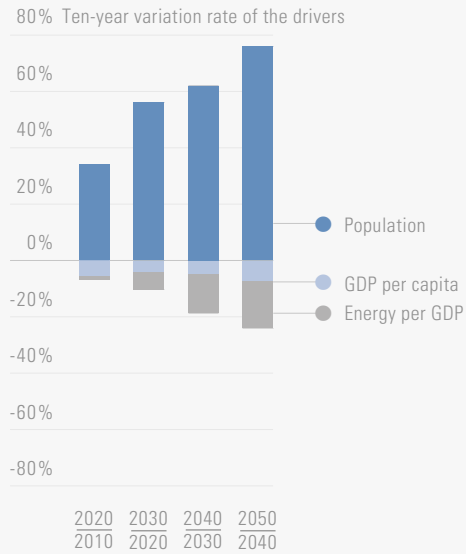
Energy Pathways, Primary Energy by source



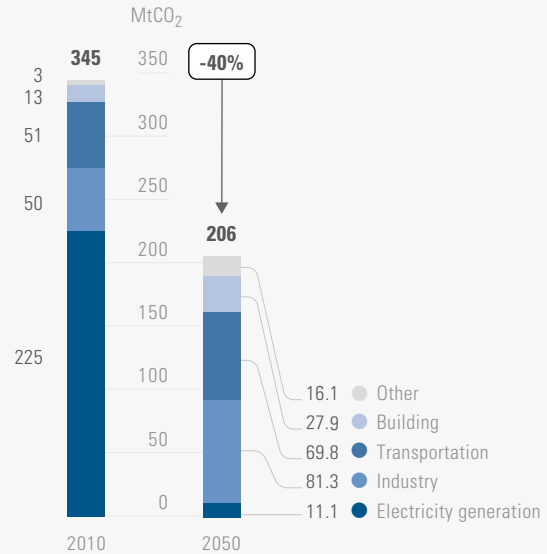
Energy Pathways, Final Energy by source



Energy-related CO₂ Emissions Drivers, 2010 to 2050



Energy-related CO₂ Emissions Pathway, by Sector



The Pillars of Decarbonization

Energy efficiency



Energy intensity of GDP, MJ/\$

Decarbonization of electricity



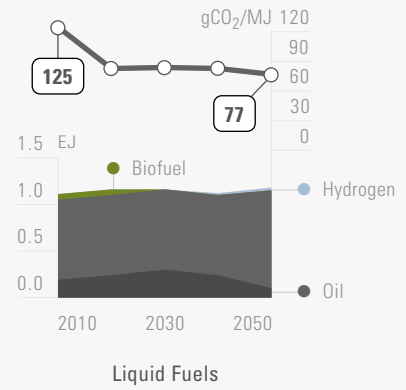
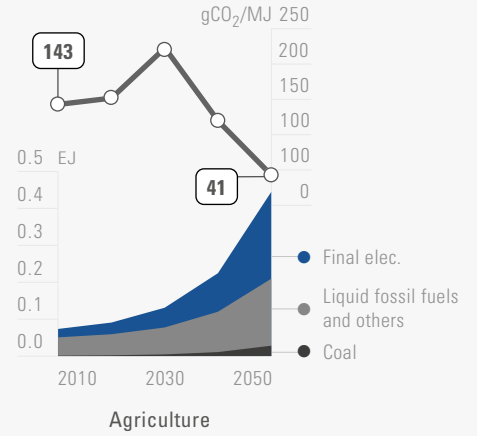
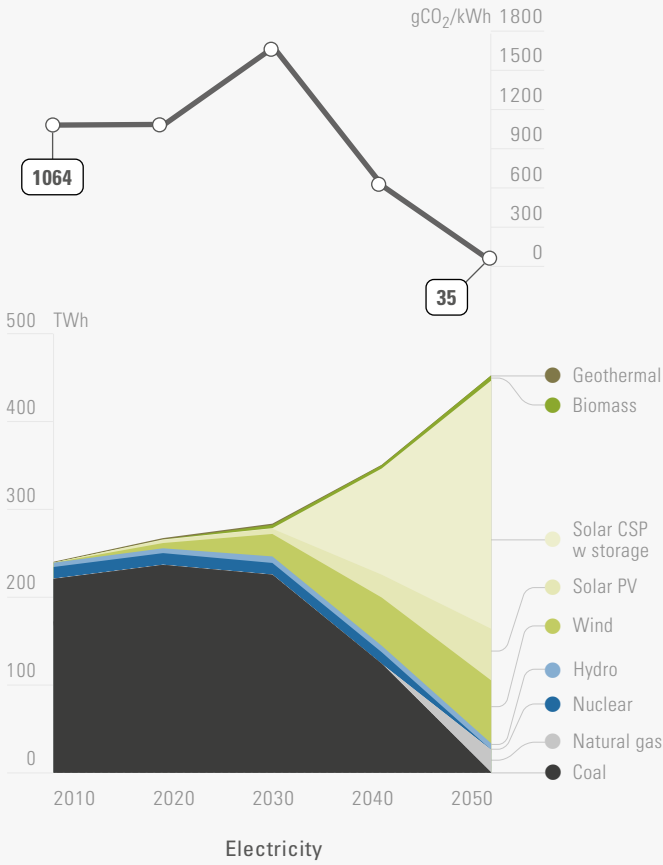
Electricity emissions intensity, gCO₂/kWh

Electrification of end-uses

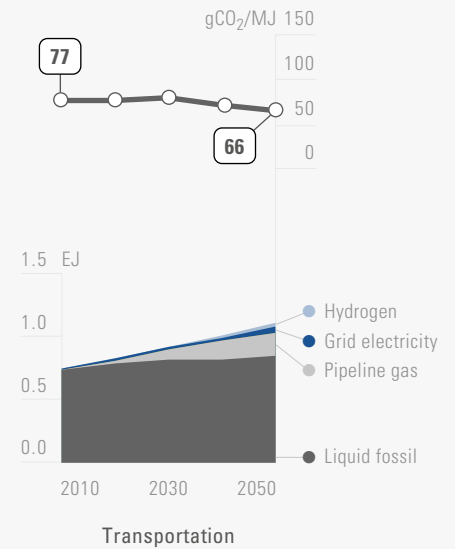
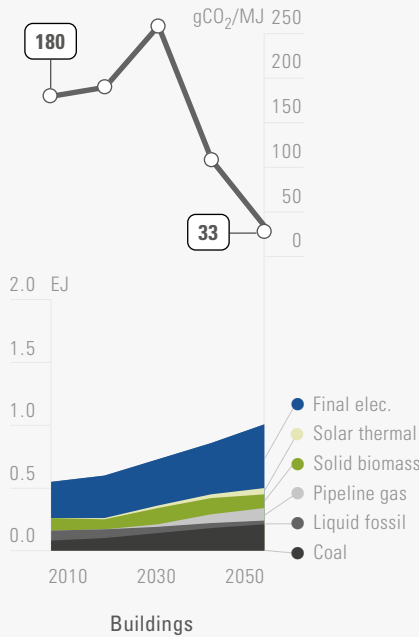
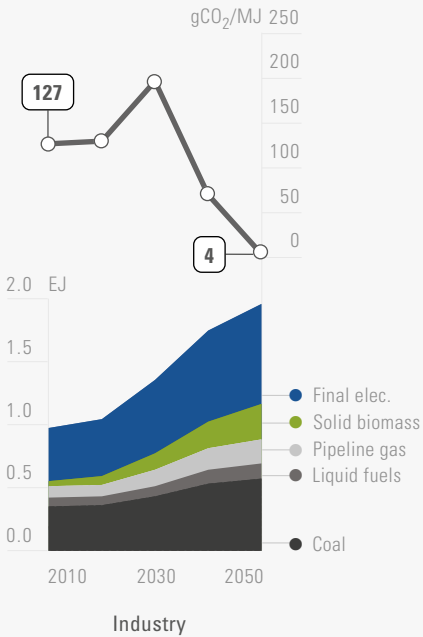


Share of electricity in total final energy, %

Energy Supply Pathways, by Resource

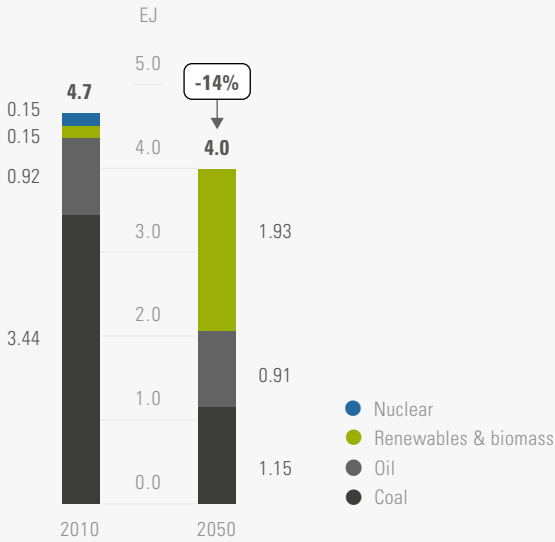


Energy Use Pathways for Each Sector, by Fuel, 2010 – 2050

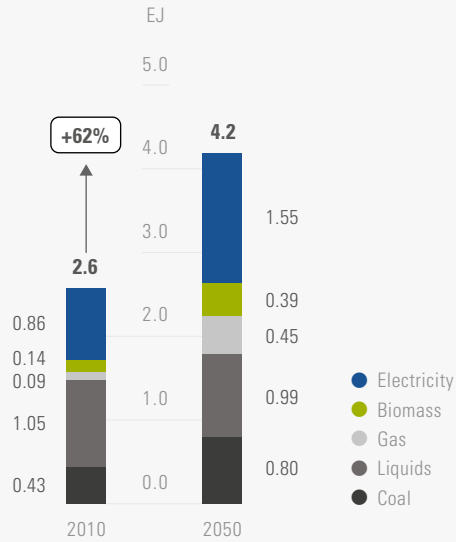


ZAF – High Skills

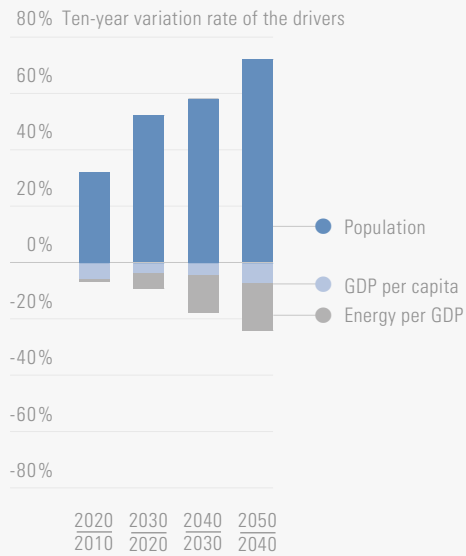
Energy Pathways, Primary Energy by source



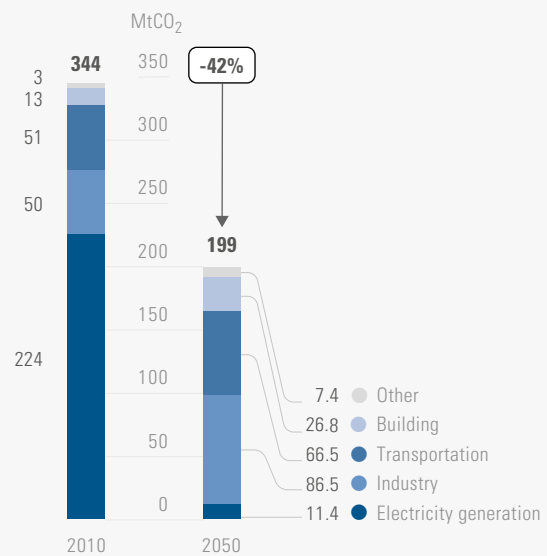
Energy Pathways, Final Energy by source



Energy-related CO₂ Emissions Drivers, 2010 to 2050



Energy-related CO₂ Emissions Pathway, by Sector



The Pillars of Decarbonization

Energy efficiency



Energy intensity of GDP, MJ/\$

Decarbonization of electricity



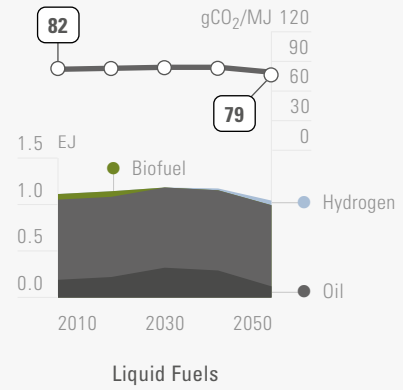
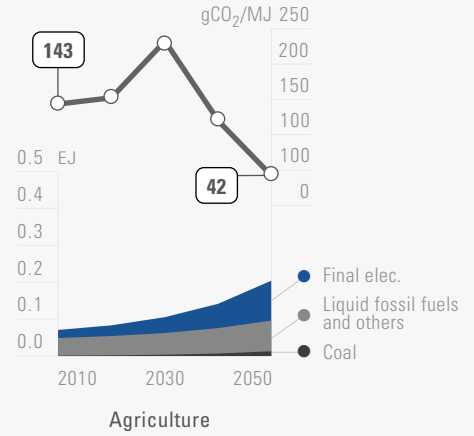
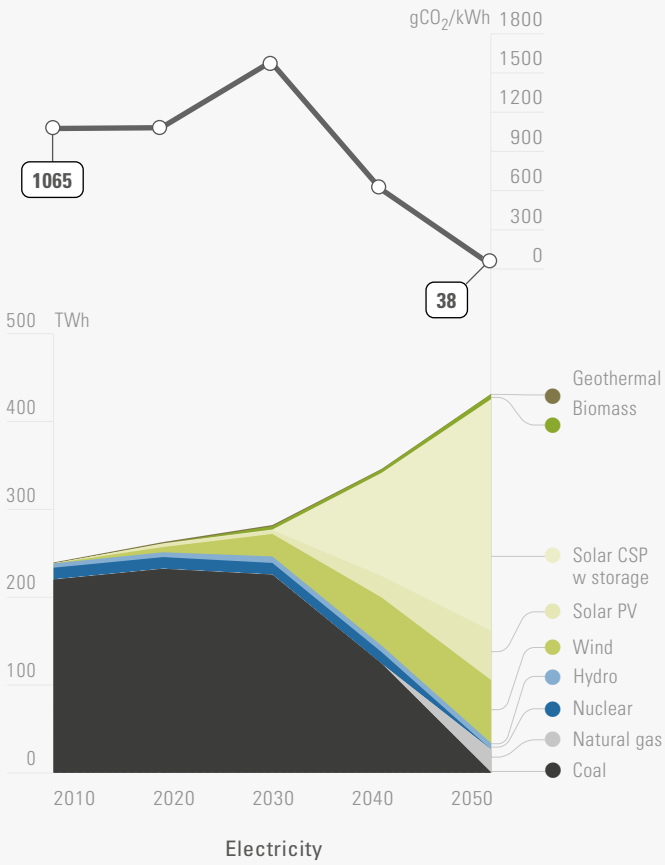
Electricity emissions intensity, gCO₂/kWh

Electrification of end-uses



Share of electricity in total final energy, %

Energy Supply Pathways, by Resource



Energy Use Pathways for Each Sector, by Fuel, 2010 – 2050

