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Effects of decarbonization on the energy system and related employment effects in South Africa

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ABSTRACT

This paper assesses the impact of decarbonization on the energy system and related employment in South Africa. The cost-minimizing, global energy system model (GENeSYS-MOD) is utilized to project two energy mix scenarios and their associated employment implications at provincial level. While the business as usual (BAU) scenario shows a continuous use of coal capacity in the South African power sector until 2050, the 2 °C scenario exhibits a phase-out of coal by 2040 and a higher diversification of power generation dominated by solar and wind capacity.

The increase in renewable energy sources (RES) generates employment in the energy sector which can partially substitute the decline in coal related jobs in affected regions. However, it is not certain that the employment created by RES will directly benefit those negatively impacted by the transition. The results of a sensitivity of the 2 °C scenario provide a near cost-optimal energy system in line with a just transition towards a 2 °C world that limits the employment impacts for former coal regions. Thus, a technological transition from a coal- to a RES-based system needs comprehensive plans for job-transfers, policy formulations, support mechanisms and structural transformation.

1. Introduction

The worldwide commitment to decrease greenhouse gas (GHG) emissions to stay within a 2 °C pathway implies the need for a phase-out of fossil fuels and especially coal. The consequential decrease of coal demand on the global market and the obligation to reduce emissions on a national level will greatly affect carbon intensive countries like South Africa (Burton et al., 2018a; International Energy Agency, 2019c; IPCC, 2018). With its total primary energy supply and power generation dominated by coal with 74% and 87% respectively, resulting emissions are accordingly high (463 MtCO_2 in 2017) (Global Carbon Atlas, 2019; International Energy Agency, 2019b; Climate Transparency, 2018). Additionally, South Africa is the sixth largest steam coal exporting country in the world (International Energy Agency, 2019a) and the economic income and national employment structure highly depend on mining of and trade with coal (Burton et al., 2018a). As a country dealing with high unemployment and extreme poverty, it will face financial, technological and social challenges as the transition towards a low-carbon energy system progresses (World Bank Group, 2019a; Statistics South Africa, 2018).

In order to take advantage of its high potential for solar and wind power (Hermann et al., 2014), the energy sector needs to be restructured to a renewable energy sources (RES) based energy system, requiring high investments and political commitment. Furthermore, a low carbon energy transition in South Africa is strongly linked to socioeconomic factors (Ministry of Foreign Affairs - Netherlands, 2019). Particularly jobs and revenues related to coal deployment lead to dependencies of different aspects which need to be considered to allow for a just transition.

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1.1. The relevance of coal in South Africa's energy system and the low carbon transition

South Africa has the 5th largest recoverable coal reserves in the world. Most of the coal reserves are situated in the province Mpumalanga, which is responsible for more than 80% of coal mining in South Africa (Burton et al., 2018a). However, coal mines are running out of resources, while new mining basins face significant commercial and infrastructural challenges related to water supply and rail connections (The Green House et al., 2013). Apart from its local use, South Africa exports 25–30% of extracted coal. As the coal demand in Europe decreases, 81% of South African coal exports are being shipped to Asia, especially India (Burton et al., 2018a; International Energy Agency, 2017).

Nonetheless, the use of fossil fuels is actively supported by South Africa's government in order to reach its key objectives related to energy security and economic development (Burton et al., 2018b). At the centre of this stands the state-owned monopoly power utility Eskom, as the major actor in the minerals-energy complex (MEC) of South Africa, being responsible for 95% of electricity generation, and the majority of transmission and distribution (Ministry of Foreign Affairs - Netherlands, 2019; Ting and Byrne, 2020; Baker, 2015). Despite its efforts, South Africa faces a supply-side crisis which is reflected in an inability to meet demand at all times, resulting in power outages (load-shedding). Eskom has been unable to provide adequate operational performance on the technical and financial side as a result of governance and operational misdemeanours over the past decade (Department of Public Enterprises - South Africa, 2019; Ting and Byrne, 2020). An important reason for this was the missing investments in new coal power plants and failed liberalisation of the power sector (Baker et al., 2014). Furthermore, Eskom will have to decommission an estimated 11 GW of its 40 GW installed coal capacity until 2030 as coal plants are reaching the end of their operating lives and will become too costly to maintain and run (Department of Energy - South Africa, 2019). This will further jeopardize security of supply. As Eskom suffers from financial drains and high debts, investors have to face high risks (Ting and Byrne, 2020; Baker et al., 2014; Huxham et al., 2019). Generally, finance for long-lived carbon-intensive infrastructure is becoming more difficult to find (The Green House et al., 2013). This situation is further exacerbated by political lock-in effects and fossil fuel subsidies that stand in the way of the potential of renewable energies and an energy system transition (Burton et al., 2018b; Ting and Byrne, 2020; Baker, 2015; Huxham et al., 2019).

In light of the current state of the power system and the uncertainties regarding coal, South Africa took first steps to initiate structural change in the electricity system. To counteract the trend of high emission energy production, frameworks and policies to accelerate the transition towards renewable energies were ratified. In the nationally determined contributions (NDCs), South Africa commits to mitigate its GHG emissions to a range between 398 $MtCO_2e$ and 614 $MtCO_2e$ over the period of 2025–2030. While the upper range of the target does not correspond to the goal of staying withing a 2 °C pathway, the lower range could very well achieve that (Climate Transparency, 2018). The NDC follows the peak, plateau, and decline trajectory (PPD): emissions peak between 2020 and 2025, plateau for a decade, and decline afterwards (Burton et al., 2018a; Republic of South Africa (RSA), 2016).

In addition to the introduction of feed-in tariffs in 2009 (Meyer-Renschhausen, 2013; Krupa and Burch, 2011), support for an energy transition was set as a goal in the IRP initiated in 2011, which includes a long-term plan for the energy sector (Department of Energy - South Africa, 2019). Besides decommissioning of existing coal power plants, the recent IRP 2019 further intends to build new RES capacity among others. Part of the plan is to add 6 GW of PV capacity, 14 GW of Wind capacity, but also 3 GW of gas and diesel capacity, as well as 1.5 GW of additional coal capacity until 2030 (Department of Energy - South Africa, 2019). Moreover, the possibility of increasing hydro power imports in the future is also acknowledged, as water scarcity is a continuous topic of importance in South Africa (Donnenfeld et al., 2018; Pegels, 2010). However, no further coal capacity are planned after 2030 with the aim of decommissioning 35 GW of coal power plants until 2050 (Department of Energy - South Africa, 2019). As for nuclear power, the IRP 2019 states nuclear as a “no regret” option. The lifetime of the Koeberg nuclear power plant is expected to be prolonged by another 20 years, while simultaneously increasing its original capacity (Department of Energy - South Africa, 2019). In addition, planning for the procurement of 2500 MW of new nuclear generation additions began at the end of 2020 (World Nuclear News, 2020).

Through an implemented public procurement program, the Renewable Energy Independent Power Producer Programme (REIPPPP), a ceiling tariff level for technologies in auctions was established and Power Purchase Agreements (PPAs) were given to winners with the aim to increase RES capacity (Independet Power Producer Office, 2018). Furthermore, the carbon tax was implemented in 2019 after first being discussed in 2015 (Curran, 2018; Nong, 2020). There is criticism regarding the effectiveness of the tax due to the exceptions for up to 90% of emissions by companies in certain sectors.

In line with new frameworks and policies supporting RES, current quantitative research on the South African energy sector demonstrates the trend towards an RES based energy mix in the future. All results show a coal phase-out as well as an immense increase in RES with different shares of photovoltaics (PV) and wind (IRENA, 2013b; Oyewo et al., 2019; Jacobson et al., 2017; Wright et al., 2017, 2019; Teske et al., 2011; Sager, 2014) due to different model environments and assumptions (e.g. cost development) within the calculations. Results calculated by Oyewo et al. (2019) e.g. show that by 2050, PV would be the primary contributor to the electricity generation, whereas Merven et al. (2018) present an energy mix with a more even share of PV and wind generation.

1.2. The socioeconomic impact of coal deployment and coal-exit

The energy transition will highly affect economic and employment aspects. While being the second largest economy on the African continent and ranking fifth in terms of GDP per capita (World Bank Group, 2019b), South Africa has the highest GINI coefficient in the world pointing out the vast inequality (World Bank Group, 2019a). Additionally, the high national unemployment rate of 26.7% (narrow definition) and 36.7% (broad definition) in 2018 (Statistics South Africa, 2018) makes job losses an especially sensitive topic both politically and socially (Burton et al., 2019). Consequently, energy policies need to also be considered from the perspective of equity, employment, and social justice.

In 2015, around 77,000 workers were employed in the coal mining industry, representing roughly 0.5% of the total workforce. Since the peak of nearly 140,000 jobs in the early 1980s, the total workforce in the coal mining sector has been receding. The decline is tied to the increased mechanization and automatization of mines over the years. Therefore, coal mining jobs have already been in danger for several decades and the trend will continue whether a coal-exit will be pursued or not (Strambo et al., 2019b; Cosbey et al., 2016). Overall, Eskom employs 47,000 workers in distribution, 15,000 in generation, and 10,000 in transmission and other corporate in the electricity sector, with coal accounting for the largest share (Merven et al., 2019).

In addition to the direct employment generated by coal mining, the industry also contributes to growth and employment in other sectors (e.g. transport sector, machinery, and finance service) (Strambo et al., 2019b). It is also important to consider that mining companies often directly provide services to employees and local communities by funding utilities such as housing, water, and sanitation (Strambo et al., 2019b). Therefore, cutting back coal mining will have a severe impact on employment and the communities.

While coal mining alone contributes only 2.3% to the national GDP (Strambo et al., 2019b), in the main coal mining province Mpumalanga it is one of the most important contributors to the value of goods and services produced, accounting for 19% of the gross value added (GVA)

(Strambo et al., 2019b). Within the province, coal mining is concentrated in only a few municipalities, making these communities particularly vulnerable to mine closures (Burton et al., 2019). The local consequence of a decrease in mining activity is often tied to socioeconomic erosion. Due to the narrow skill base of the workforce,[1] alternatives in employment can be hard to find and create (Nel et al., 2003). This situation negatively impacts the workers sense of identity and creates problems reaching across economic sectors and generations (Caldecott et al., 2017). Local resistance from unions to protect coal workers, political dynamics, and social destabilization can impede the transition and is therefore a major challenge of the energy transition (Burton et al., 2019; Strambo et al., 2019b). Consequently, when looking at the energy system, questions about social acceptance have gained momentum over the last years (Baker et al., 2014; Huxham et al., 2019; Burton et al., 2019).

Trade unions highlight the need of alternative employment opportunities, calling for a "just transition" (Burton et al., 2019). While the idea of a just transition is embedded in South Africa's climate policy, there are no detailed sector specific concepts for coal companies, workers, or communities (Burton et al., 2018a). The National Employment Vulnerability Assessment (NEVA) and the Sector Job Resilience Plans (SJRPs) are instruments created by the government to conduct a just transition to a low carbon economy.[2]

To assess the job trends in the transformation process, calculations considering different technologies as well as different approaches have been made addressing the employment effects on a national level (Burton et al., 2018a; Oyewo et al., 2019; IRENA, 2017, 2018; Rutovitz, 2010; Okunlola et al., 2019; Altlerl et al., 2015; Hartley et al., 2019; Bohlmann et al., 2019). Oyewo et al. (2019) and Rutovitz (2010) use an employment factor approach to analyze direct job losses and job gains during a transition. While jobs in the coal sector are decreasing, new jobs are established in the RES sector. Furthermore, Hartley et al. (2019) analyze the economy wide-impacts of an increase in RES for the South African economy. They show that the increase in RES deployment has a positive impact on gross domestic production (GDP) and employment.

1.3. Focus of the study

The prevailing literature shows that the South African energy transition is influenced by technical and economic aspects as well as social and political implications (Baker et al., 2014). The focus of this study lies on the low carbon transition by analyzing pathways from the point of the cost-minimizing Global Energy System Model (GENeSYS-MOD) developed by Löffler et al. (2017). The resulting development of employment is calculated using the employment factor approach defined by Rutovitz et al. (2015). Thus, techno-economic modelling is combined with the socioeconomic consideration of employment numbers. The analysis is executed on a regional level (including all 9 provinces) which extends the studies conducted by Oyewo et al. (2019) and Rutovitz (2010). The aim of this paper is to bridge the gap between the technical evaluation of low carbon pathways and their direct effects on the employment sector. Furthermore, we contribute the current literature on modelling exercises of the South African energy transition by providing a state-level disaggregation. A special focus is set on the coal dependent province Mpumalanga and the related necessary contributions to a just transition by taking into account coherent economic, social, and political implications.

The following section outlines the methodology, the mod-el approach using GENeSYS-MOD, and the inclusion of the employment analysis. Subsequently, the model results for the two scenarios are presented and discussed in Section 3. The paper concludes with a summary of the findings in Section 4.

2. Methodology

This paper uses the open-source Global Energy System Model (GENeSYS-MOD) by Löffler et al. (2017) and introduces an extension for socioeconomic employment analyses.

2.1. GENeSYS-MOD

The primary objective of GENeSYS-MOD is the minimization of the net present cost of an energy system to meet the given demands, encompassing sector-coupling decisions across the sectors electricity, heat, transport, and industry. This makes the model a powerful tool to create pathways for the energy transformation. To do so, the linear model uses a variety of equations, which serve as constraints, to find an optimal least-cost solution. Applications of the model include country level case studies (Burandt et al., 2019; Bartholdsen et al., 2019; Sarmiento et al., 2019; Lawrenz et al., 2018) as well as macro-regional and global scope analyses (Löffler et al., 2017, 2019; Hainsch et al., 2018).

Energy demand within the model is split into the following categories: electricity, residential heating, industry (low-temperature, medium-temperature, and high-temperature process heat demands), and transportation (passenger and freight transport demand). The model chooses combinations of technologies, storages, and trade between the different regions to meet the given energy demands for each region and timeslice.[3] This process is subject to multiple, complex considerations such as costs, energy potentials, location, and the grid situation amongst others. For this study, we chose a time resolution of roughly 120 time slices per year, yielding a model that offers full sectoral interlinkages, a time horizon of 2015 to 2050, as well as high detail in intra-yearly temporal resolution. For further information about the model and its mathematical and technical implementation, please refer to Appendix A as well as Löffler et al. (2017), Burandt et al. (2018), and Burandt et al. (2019).

We partitioned South Africa into nine regions in accordance to its official provinces (see Appendix A). The energy system optimization includes the years 2015 to 2050 in 5-year-steps, with 2015 serving as a baseline, considering existing power plant capacity and network interconnections. Additionally, we added 2017 as an intermediate year to further validate the short-term model workings.

The model calculation needed a substantial amount of data, including the energy system, as well as the employment analyses. As for general technology data, we took values from previous case studies (Burandt et al., 2018, 2019) and adopted them with more detailed regional data for South Africa (see Appendix B for an overview of the used data). Where no regional resolution is available, we have adjusted the data to the regions. For the capacity, we assigned the national capacity for the technologies we used the percentage area of the states to assign the national capacity data to the states. Furthermore, for the demand assignment to the states we use the population distribution.

2.2. Embedded employment analysis

In order to enable the examination of the employment effects that come with a low carbon transition, an employment analysis module has been added to GENeSYS-MOD. This allows to monitor job additions, changes, and losses, and enables the use of constraints (such as lower

[1] In 2015 high skilled workers represented 10% of the coal-workforce, 35% were mid-level workers, and 56% were semi- or unskilled workers (Burton et al., 2018a).

[2] As stated in the National Climate Change Response White Paper (Department of Environmental Affairs, 2018), NEVA will assess what job-related interventions may be required and where they may be required, while ministries will be developing the SJRPs in order to explore sectoral job creation opportunities (Strambo et al., 2019b).

[3] Timeslices are representative hours of a full year, achieved via a time series clustering algorithm, as described in Burandt et al. (2019).

bounds). We use the employment factor approach by Rutovitz et al. (2015), measuring direct jobs during the energy transformation.

The analysis takes data for energy production, installed capacity, and employment factors, with the employment factor as the focal point – giving the number of full time job equivalents (FTE) per GW for each technology (IRENA, 2013a; Rutovitz et al., 2015). This can be segmented into manufacturing, construction and installation (C&I), operation and maintenance (O&M), and fuel supply for one unit of generation capacity per year. Manufacturing and C&I jobs are temporary, only remaining for the corresponding period during which capacity are being build. Furthermore, a fixed duration for the setup of power plants, depending on the technology type, is considered. The model's original output unit of manufacturing and C&I jobs is given in job years. Under the assumption that the manufacturing and C&I of new capacities is equally distributed among the years of each time slice, the job years of each time slice were transformed into yearly FTE in a given 5 year period (or two and three years for the 2015-2017 and 2017-2020 time slices, respectively). In contrast, O&M jobs associated to certain capacity are considered permanent for the whole lifetime of the installed power plant. The number of O&M jobs depends on the running capacities and is given in FTE per GW. Fuel supply jobs take the primary energy demand as well as export demand into account. The amount of jobs therefore varies depending on these demands and is given in FTE per PJ. A decline factor serves to include the learning adjustment rates over time for each technology and a local manufacturing factor is included for the manufacturing jobs (Rutovitz et al., 2015). The employment factor is then multiplied by the capacity or generation (IRENA, 2013a).

The input data for the employment analysis is based on the model results of GENeSYS-MOD for the nine South-African regions, combined with employment values from literature, and projections for the development of coal exports. The employment values are based on Rutovitz (2010), Rutovitz et al. (2015) and Ram et al. (2020). Furthermore, we used the data from Rutovitz (2010) which uses the employment factor approach with a regional adjustment factor for South Africa, to calibrate the values to the actual regional specificities of South Africa. Appendix C describes the procedures towards determining the data, sources and further details for the employment analysis and Appendix A details the data for the employment analysis.

2.3. Scenarios

The paper analyzes and compares two scenarios. The BAU scenario does not enforce any climate targets and follows current trends of a fossil fuel based power production. It has no CO_2 budget, but implements current plans of a carbon tax by the South African government as a constraint (Curran, 2018). Additionally, for coal exports, the BAU scenario relies on the hard coal export projections based on the new policies scenario by the International Energy Agency (2017).

The 2 °C scenario, however, is linked to the Paris Agreement. To set the emission limit, a per-capita approach of distributing the CO_2 budget was used based on Hainsch et al. (2018). Based on that methodology, the budget for South Africa is 5.35 $GtCO_2$ for 2015-2050, taking into account its population share.[4] Furthermore, the assumption that the rest of the world also follows a 2 °C pathway and therefore reduces coal imports was made. Assumptions on South Africa's coal exports are based on the results for the 2 °C_noCCTS scenario in Mendelevitch et al. (2019), who applied the global steam coal market model COALMOD-World.

Both scenarios use the embedded employment analysis to evaluate changes for workers in the energy sector, especially in the coal sector.

[4] There are different ways to distribute the global carbon budget taking into account fair share calculations, e.g. emission per capita, per GDP, share by current emissions or past emissions (see Hainsch et al. (2018) for further explanation). For this study, however, we chose the per capita approach.

In addition, we apply a sensitivity analysis of the 2 °C scenario focusing on employment effects. The sensitivity analysis underlines the need to manage a socially acceptable energy transition – especially for workers in the coal sector. It preserves the amount of jobs in the energy sector in every region above the 2015-level at all times in order to provide new employment opportunities for coal workers. This results in a near cost-optimal 2° scenario which is politically more acceptable.

3. Model results

The following section presents the model results for the BAU and the 2 °C scenario and highlights the differences.

3.1. Results for the energy sector

Currently, the South African energy sector is dominated by fossil fuels. Approximately 90% of electricity is generated by coal, which also dominates the heating sector, whereas the transport sector is mainly fueled by petrofuels. Due to the rising competitiveness of renewables and environmental restrictions, both scenarios show rising shares of RES across all sectors. As displayed in Fig. 1, the use of RES in the 2 °C scenario increases substantially in all sectors in comparison to the BAU scenario.

Of all three sectors, the power sector achieves the highest transition rate of renewable energies overall. While coal still accounts for 20% of total power generation in the BAU scenario in 2050, the 2 °C scenario achieves a share of 100% RES to stay in line with the carbon budget. The relatively small amounts of nuclear and natural gas power phase out by 2040. A main factor for this development is the cost difference of the technologies and fuels. The model uses existing coal capacity in the first decades. Costs for RES decrease rapidly as the technologies advance and the set carbon budget in the 2 °C scenario limits the use of further fossil fuel technologies.

The trend towards more RES can also be noted in the transport and heating sector. However, decarbonization of these sectors is most cost efficient using electricity based technologies, resulting in increased sector coupling. Therefore, electricity quickly becomes the dominant energy source used in the transport sector with a share of around 59% in the BAU scenario and around 79% in the 2 °C scenario in 2050. The share of direct use of RES in the transport sector is around 9% in the BAU scenario whereas the 2 °C scenario displays a share of 17% by 2050.

As opposed to the BAU scenario with 40% still being petrofuel-based in 2050, the 2 °C scenario exhibits a nearly complete shift away from crude oil derivatives in the transport sector. Furthermore, in the heating sector, RES show a share of around 42% in the 2 °C scenario. Nevertheless, due to the 2 °C carbon constraint, the sector fully decarbonizes with around 58% electricity used, whereas coal dominates the sector in the BAU scenario (85%). In order to analyze the transition with regard to employment effects, the focus of the results lies mainly on the power sector.

Table 1 shows the installed capacity and newly added capacity for both scenarios over the given time period as well as for the employment sensitivity, which will be discussed later in Section 3.3. Both main scenarios exhibit an increase in RES capacity, especially wind and PV, and an increase in storage capacity, particularly lithium ion (LI) battery storage. However, the 2 °C scenario has double the increase in new capacity compared to the BAU scenario. It needs to be noted that the amount of newly build capacity is higher than total capacity, especially in the 2 °C scenario due to the early build up of RES capacity and their decommissioning in the time period. Coal capacity significantly decreases in both scenarios while no nuclear and gas capacity remain by 2050.

Both scenarios exhibit a rise in power production due to an increasing demand and sector coupling (see Fig. 2). Coal power production in the BAU scenario increases to 268 TWh in 2030 and only then steadily declines until reaching 94 TWh in 2050. In contrast, PV and

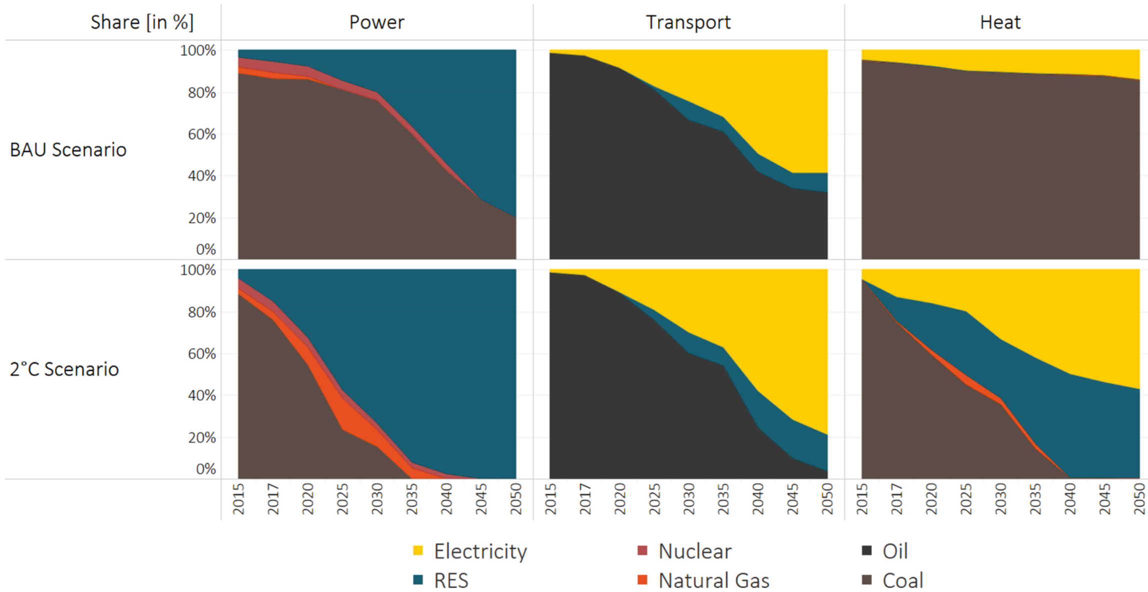

Fig. 1. Comparison of sectors in South Africa between the BAU and the 2 °C scenario. Source: Own illustration.

wind show increasing shares, reaching 247 TWh and 123 TWh, respectively. This effect is most present in the years from 2030 onwards, as RES prices continue to decline. Small amounts of natural gas and nuclear power exit the power mix by 2025 and 2040. The 2 °C scenario generally exhibits a higher power production due to increased sector coupling. In the 2 °C scenario, coal power production is decreasing rapidly until its phase out by 2035.

Conversely, power production from PV increases to around 306 TWh in 2050, whereas power production from wind onshore increases to 369 TWh in 2050. While in the BAU scenario PV is predominant, wind power plays a bigger role in the 2 °C scenario. Furthermore, due to high initial costs and lower cost reduction, wind offshore enters the power mix only by 2045. Hydropower stays at a relatively constant level from 2025 onwards as most of the limited available potential is deployed by then. Small amounts of biomass power remain in the mix until 2050 in both scenarios. Similar to the BAU scenario, gas and nuclear energy exit the power mix by 2030 and 2040, respectively.

Regarding the allocation of power production, coal power production in 2015 highly concentrates in Mpumalanga and to small degrees in Limpopo, Free State, and Gauteng. As illustrated in Fig. 3, the power production diversifies and decentralizes in both scenarios over the given time period.

This is mainly due to the decentralized character of RES. Nonetheless, Mpumalanga still displays a high concentration of coal power production in 2050 in the BAU scenario. Opposed to that, the 2 °C scenario shows a substantial increase in RES until 2050 in all regions.

3.2. Results for the employment analysis

In the following, the results for the job distribution in South Africa's energy sector are presented to show the energy transition's impact on the structure of the employment sector.

As illustrated in Fig. 4, both scenarios display a considerable increase in employment, while the BAU scenario displays lower overall numbers. The creation of new jobs in both scenarios is mainly caused by the build-up of solar and wind power capacity. Total numbers in the BAU scenario rise moderately from an initial 110,000 jobs to 180,000 jobs in 2035 and then steeply increase to 468,000 jobs in 2050.

In contrast, the 2 °C scenario exhibits a fast increase in jobs, reaching its peak of around 630,000 in 2040. Noticeable is the loss of jobs in

Table 1
Comparison of total and new power capacity additions in the BAU scenario, 2 °C scenario and the employment sensitivity (ES). The new capacities are given over the entire modeled time period and include replacement of end-of-lifetime generation capacities.

	Total capacity (GW)				New capacity (GW)		
	2015	2050			2020-2050		
		BAU	2 °C	ES	BAU	2 °C	ES
Photovoltaics	1.21	126.14	168.16	160.25	128.38	199.88	191.79
Wind onshore	1.09	36	115.92	131.73	43.2	143.23	159.21
Wind offshore	0	0	5.04	2.42	0	5.04	2.42
Biomass	0.46	0.05	0.11	3.05	0	0.07	3
Hydro	0.86	1.27	5.92	5.97	0.19	4.8	4.85
LI battery storage	0	61.6	110.5	103.87	80.31	177.97	168.01
H^2 storage	0	0.3	2.48	2.65	0.29	2.48	2.65
Pumped hydro storage	2.4	0.68	0.37	0.37	0.35	0.04	0.04
Nuclear	1.94	0	0	0	0	0	0
Natural Gas	3.65	0	0	0	0	0	0
Coal	48.06	12.74	11.13	11.13	6.79	5.17	5.17
Total	59.67	238.78	419.63	421.44	259.51	538.68	537.14

Source: Own illustration.

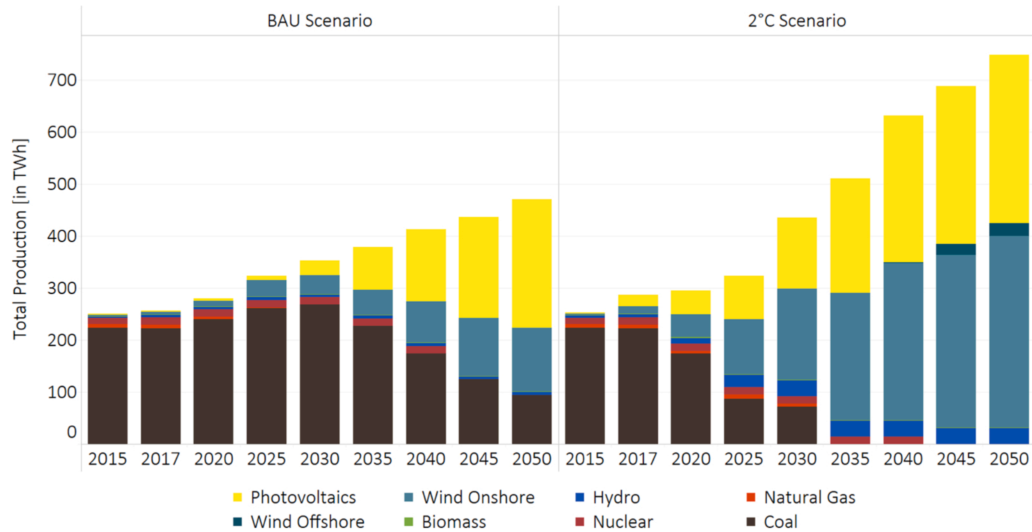

Fig. 2. Total power production in South Africa. Source: Own illustration.

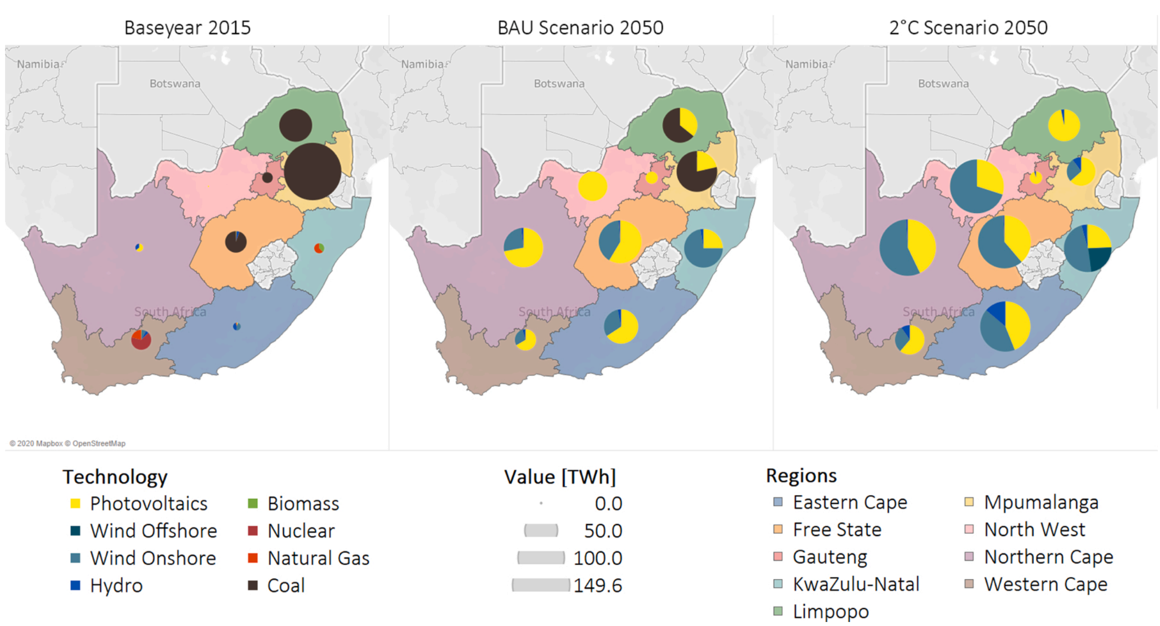

Fig. 3. Regional power production in South Africa. Source: Own illustration.

2045, caused by a decrease in C&I and manufacturing jobs as less new capacity are installed in 2045. Nevertheless a rise back to 594,000 jobs can be observed in 2050. Overall, PV create the most jobs across both scenarios in 2050.

In accordance with the regional power production, jobs are distributed more evenly across the country at the end of the model period. However as can be seen in Fig. 5, the 2 °C scenario shows higher numbers of jobs throughout the whole country compared to the BAU scenario in 2050. This disparity is due to the higher build-up of RES in the 2 °C scenario as mentioned earlier.

Since the South African energy sector mainly relies on coal in 2015, the coal regions and especially Mpumalanga show the highest number of jobs in South Africa in the early years of the analysis (see Fig. 5). Due to the continuous use of coal in the BAU scenario, these regions still have a fair amount of coal jobs in 2050. In the 2 °C scenario however, the number of jobs drop below the level of 2015 in Mpumlanga from 2030 onwards. This is due to the coal phase-out and the loss of fuel supply jobs, which outweigh the jobs created through installation of new RES capacity (see Appendix E.4).

For further understanding of the results, figures regarding capacity, industry heating sector, emissions, and employment can be found in Appendix E.1, E.2, E.3, and E.4 respectively.

3.3. 2 °C scenario employment sensitivity

The employment results for the 2 °C scenario show an increase in jobs in the energy sector in nearly all regions except for the province Mpumalanga that is most dependent on employment related to coal. Consequently, a sensitivity analysis was conducted with the constraint to keep the net number of jobs above the level of 2015. This yields a near cost-optimal energy system in line with a 2 degree world which still allows for sufficient job possibilities in former coal regions. The total increase in system costs for these measures is a 0.2% increase of total system costs compared to the 2 °C scenario, or 1.34 billion €. However,

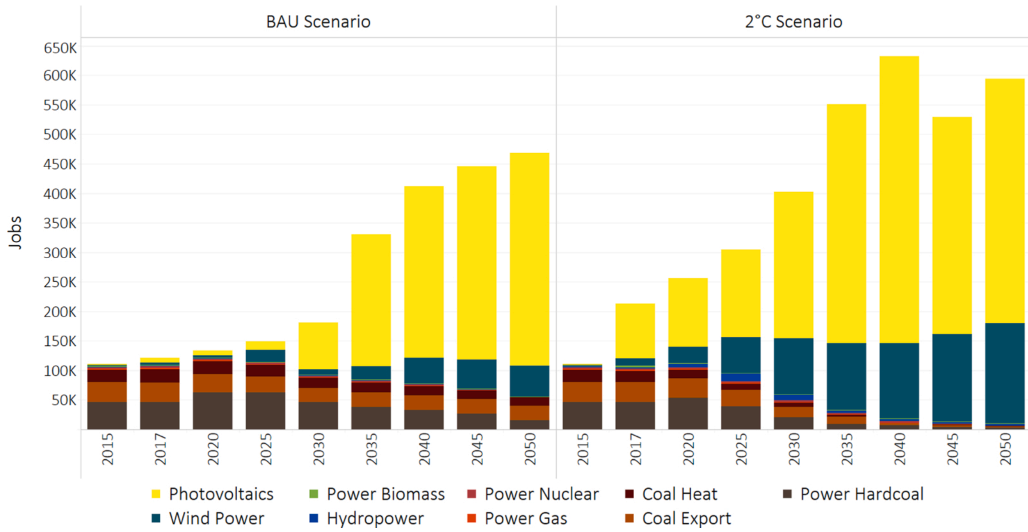

Fig. 4. Employment effect in South Africa. Source: Own illustration.

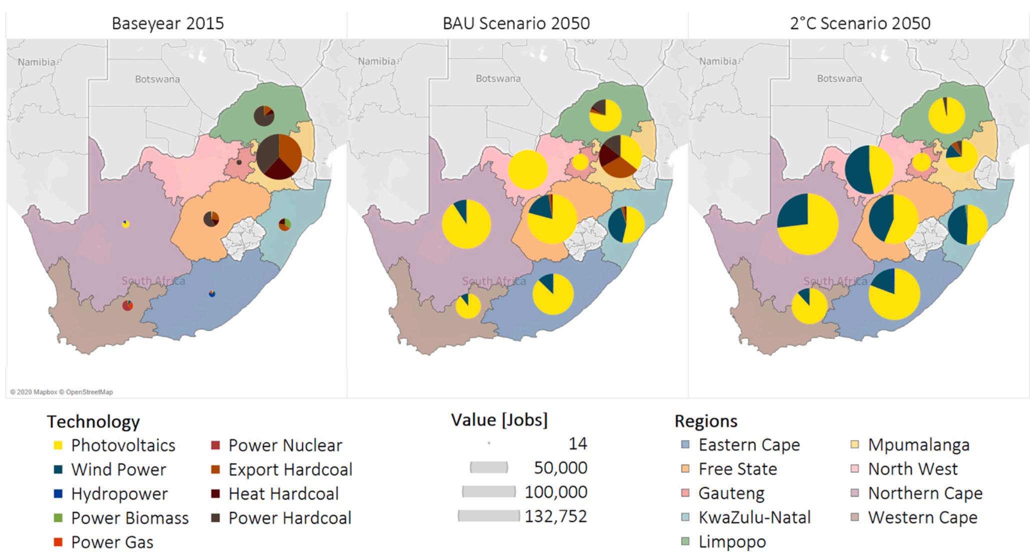

Fig. 5. Employment regional distribution in South Africa. Source: Own illustration.

at the same time, this leads to a more decentralized electricity grid, with the import dependency of Mpumalanga being 75% lower in the case of the employment sensitivity.[5]

Electricity generation costs fall across all scenarios due to the increasing cost-effectiveness of renewables, reaching between 0.04 € (0.697 ZAR) per kWh in the 2 °C scenario and 0.0422 € (0.732 ZAR) per kWh in the employment sensitivity in 2050. The BAU scenario reaches a middle ground here, reaching 0.0415 € (0.721 ZAR) per kWh in 2050. However, these only represent the pure costs of electricity generation and do not include for infrastructure costs, which would likely cause the BAU values to get slightly higher.

Results for power production and installed capacity are close to the results for the 2 °C scenario. However, there is a slightly higher total power production and total capacity in the employment sensitivity by 2050, since capacities are moved to other regions with slightly lower full-load hours for renewables. In both scenarios, PV and wind dominate power production. However, wind onshore plays a bigger role in the employment sensitivity compared to the 2 °C scenario, whereas the capacity and power production from wind-offshore is reduced (see Appendix E.5).

Similar to power production, Fig. 6 shows resembling projections in employment numbers between the 2 °C scenario and employment sensitivity. However, the biggest difference between the two scenarios lies in Mpumalanga: Due to the constraint that overall employment numbers should not be reduced in the employment sensitivity, Mpumalanga shows a higher total number of jobs compared to the 2 °C scenario. To achieve that, the model builds around twice as much capacity in Mpumalanga as compared to the 2 °C scenario, as Fig. 7 shows. While doing so, it prioritizes wind energy which reaches a total capacity of 22 GW in contrast to 4 GW in the 2 °C scenario. As a result, a marginal decrease in capacity and employment can be observed in other regions (e.g. KwaZulu-Natal, North West, Northern Cape, Western Cape).

The total job difference in Mpumalanga between the 2 °C scenario and the employment sensitivity increases from 18,000 jobs by 2030 to

[5] Net electricity imports in Mpumalanga are at 55 TWh in the 2 °C scenario and at 14 TWh in the employment sensitivity.

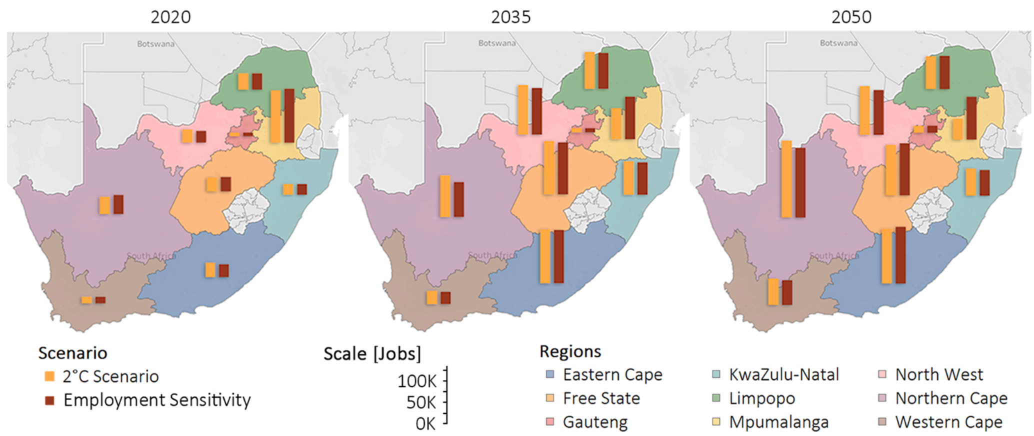

Fig. 6. Regional distribution of employment for 2 °C scenario and employment sensitivity in South Africa. Source: Own illustration.

41,000 jobs by 2050. (see Apendix E.6).These two different paths show that an energy transition without consideration of the employment structure in the energy sector can result in job losses in coal intensive regions such as Mpumalanga.

3.4. *Discussion of model results*

The model's results reinforce the need to actively plan the energy transition in line with international climate targets which implies a coal phase-out in South Africa. Following a business as usual pathway, the dependency on coal remains a major factor in the energy sector. Effective policy instruments and the cooperation of national and local actors are therefore needed in order to switch to a more diverse low-carbon pathway (Ting and Byrne, 2020; Burton et al., 2018a; Pegels, 2010; Nong, 2020). One such pathway is this paper's 2 °C scenario. The results show that a coal-phase out is possible and a nationwide implementation of RES capacity is most cost efficient within the limits of the 2 °C emission constraint. However, with the increasing electrification and related sector coupling, the demand for electricity grows rapidly and is almost 1.6 times higher than in the BAU scenario in 2050. As of now, South Africa is struggling to meet demand and ensure security of supply due to the high dependency on insufficiently managed coal power capacity and coal supply shortages (Burton et al., 2018a; Ministry of Foreign Affairs - Netherlands, 2019).

By using mainly wind and PV power, the 2 °C scenario creates a decentralized energy structure throughout the country (see Fig. 3). This reduces the provinces and communities reliance on the current coal-focused and centralized structures. Since the power supply would not rely entirely on Eskom's coal power, this could prevent power outages and stabilize the power supply throughout South Africa (Ting and Byrne, 2020). Nevertheless, investment in energy infrastructure is still necessary in light of the size and location of newly created RES-based power production. Especially in regions where little to no power was generated so far, improvement and extension of the electricity grid and other infrastructures is crucial and requires careful planning and support by the government. The model considers both investments into an expansion of the electric grid, or a more decentralized placement of generation capacities within the states as viable options. It therefore weighs the costs of grid infrastructure investments against potentially less favorable capacity factors for RES. In total, roughly 2 billion € are invested in new transmission grid capacities in the BAU scenario, whereas the 2 Degree scenario sees no increase of transmission capacities, opting for a more distributed supply throughout the country.

Furthermore, the use of mainly variable renewable energy (VRE) for power generation makes it necessary to have enough dispatchable options available. When looking at local high VRE scenarios, e.g. Klein et al. (2019) or Roff et al. (2020), the dominant dispatchable technology is gas. The results of this paper though focus on the emission free options, making storage capacity the biggest dispatchable technology. Given the electrification of the energy sector and focus on RES and storage technologies, employment in RES increases much quicker and in greater

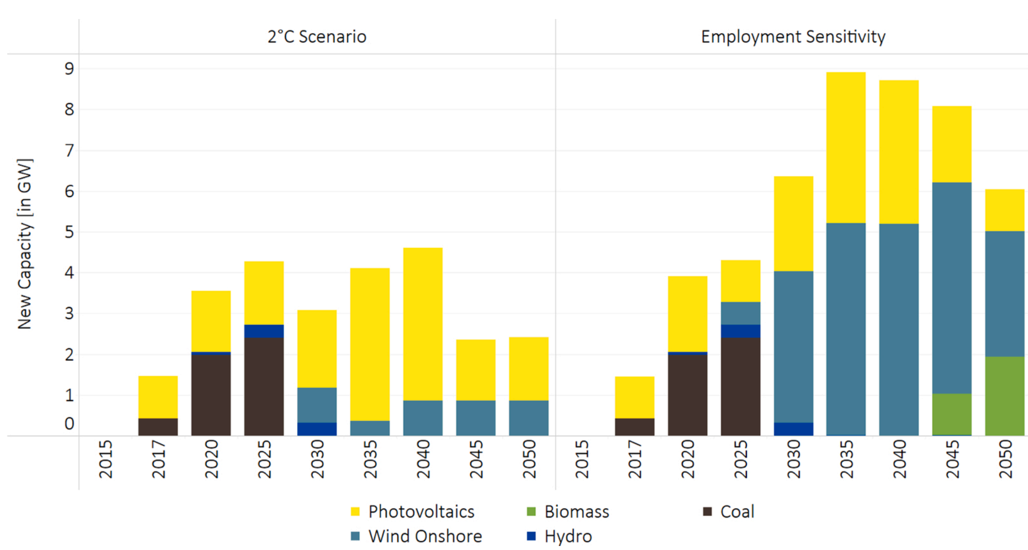

Fig. 7. Necessary capacity build-out in Mpumalanga in order to preserve current employment numbers. Source: Own illustration.

overall numbers while coal related jobs decrease faster compared to local and international analyses by e.g. Okunlola et al. (2019) and Merven et al. (2019). Since the 2 °C scenario is looking to phase out coal completely, the topic of mine closure and related repercussions such as air and water pollution gains importance as well. Although South African mining companies are obliged to set aside financial resources for environmental rehabilitation (Strambo et al., 2019a), the lack of transparency and accountability raises concerns about the risk of mining companies closing down without fulfilling their long-term obligations (Strambo et al., 2019b). Moreover, the requirements are relatively new, leaving older, abandoned mines untouched (Marais and Nel, 2016).

Regarding the overall employment numbers, the newly created jobs outweigh the job losses considerably. By switching to an RES-based energy system, power production will be more decentralized and more provinces will be able to produce the majority of power themselves. In contrast, Mpumalanga will need to reduce its coal-related mining and power production, effectively cutting its employment numbers. However, with South Africa's already high poverty and unemployment rate, it is crucial for a just transition to address such challenges (World Bank Group, 2019a; Statistics South Africa, 2018; Burton et al., 2019; Büscher, 2009). The 2 °C scenario employment sensitivity shows that net job losses in the mining sector can be compensated by RES deployment in Mpumalanga considering a near cost-optimal energy system. While RES based power production in Mpumalanga should be promoted, it is uncertain how many of these jobs will directly benefit people formerly employed in coal related fields.

Hence, when evaluating potential job alternatives for the coal-sector, it is necessary to critically scrutinize the employment results first. The model is only considering the quantity but not the quality of jobs such as the skill-level of workers and the disparity in wages. When going into more detail regarding the assessment of new employment opportunities, different aspects need to be considered to evaluate if the opportunities can be suitable. Amongst others the distribution and required skill level of existing jobs and possible substitutions are subject to critical debate and should be part of political objectives and instruments. Besides that, the age of coal worker must also be considered in political design. Furthermore, an assessment of job alternatives outside the energy sector, especially in Mpumalanga, is crucial in order to evaluate job losses and gains. Hartley et al. (2019) show how different sectors can create new job opportunities. However, for all employment alternatives it is important to consider the required skills, as jobs are not necessarily easily transferable due to the specific skill profile of the coal workers (especially coal miners) and health issues. Therefore, consideration of alternative jobs must go hand in hand with appropriate training and other (financial) support measures.

One such opportunity could be found directly in the mining sector. As the electrification of the transport sector will lead to an increase in electrical vehicle demand not only nationally but globally, the related need for batteries will increase as well (Hartley et al., 2019). As a consequence, metals used in the construction of such batteries (cobalt, copper, nickel) will be highly demanded (Alves Dias et al., 2018; Tisserant and Pauliuk, 2016). While currently none of these metals play a big role in the mining sector, the potential and availability exists.

Besides the mining sector, the focus could be on agriculture, agro-processing, tourism, as well as manufacturing (Mpumalanga Department of Economic Development, 2011). Employment opportunities in Mpumalanga's tourism sector are facilitated by the Kruger Nationalpark and by its proximity to the Johannesburg region, which provides a stable tourism enquiry (Leonard, 2016). Moreover, an innovative way of taking advantage of mine closures, while diversifying the regional economy, restoring the environment and dealing with the local history, is by developing mining- and geotourism (Oei et al., 2019; Stognief et al., 2019). This approach would use the sites of shut down mines and transform them into environmental reserves. However, the fact that the tourism sector is highly seasonal needs to be considered (Burton et al., 2018a; Leonard, 2016). Around 46% of South Africa's high potential arable land is located in Mpumalanga, where opportunities for the agriculture value chain assessments and processing hubs could be found (Strambo et al., 2019b).

Nonetheless, the overall notable amount of medium- to high-skilled level workers in agriculture (Madiba and Ka Plaatjie, 2016), manufacturing (Bhorat and Rooney, 2017) as well as in the power sector emphasize the need for retrainings and educational programs compared to the predominant low-skilled workforce in the coal sector.

However, in order for the sectors to be adequate substitutes or alternatives in the first place, working conditions need to be adapted. It is crucial to provide an environment that generates economic opportunities for workers (Caldecott et al., 2017). Important are higher wages as they are mostly lower in comparison with coal mining (Strambo et al., 2019b). Other relevant aspects include social benefits and the reliability of jobs and their payments. This needs commitment from local as well as national politics.

Furthermore, the historically established structures in the coal sector and the high identification of the workers with the coal industry set another challenge for the low-carbon transition in Mpumalanga. The NEVA and SJRP are first steps in preparing the employment sector for the coming energy transition. Further measures could include implementing and accompanying educational programs and social dialogues (Sartor, 2018). Educational programs can be related to regional specific strengths in order to maintain the local identification as well as cross-sectoral job transfers. Moreover, skill-levels could be adjusted by these programs, increasing the workforce suited for newly created, higher skill-based jobs. The regulatory framework can give financial and organizational support for the future implementation of such measures (National Planning Comission, 2019). Additionally, the unique theme of geo-mining parks could take great advantage of the heritage of the sites and deal with the identity and history of the communities as well (Dos Santos et al., 2016; Edwards and Coit, 1996).

Even then, external factors remain an uncertainty. The future of the international coal market is still unclear and demand for coal could decrease faster than expected (Oei and Mendelevitch, 2018). The COVID-19 pandemic might in addition fasten this global phase-out (Oei et al., 2020). This makes it especially crucial for coal exporters such as South-Africa to establish immediate and long-term measures, allowing for an adequate response to the approaching challenges of a low carbon energy transition.

Overall, the results show that by setting a carbon constraint South Africa can very well achieve a decarbonization of the energy sector. Moreover, the analysis also illustrates that a transition without consideration of employment aspects can have severe consequences for affected regions. Considering that the carbon constraint is only a theoretical construct, effective and efficient policies are needed immediately. The IRP 2019 facilitates an increased deployment of RES to accomplish the goals set in the NDCs. However, as the upper bound of the NDC is not sufficient to decrease South Africa's emissions to a level compatible with a 2 °C pathway, the scheduled revision of the NDCs in 2020 should aim for more ambitious goals (Climate Transparency, 2018). This includes intensifying already existing as well as new approaches and regulations to support an energy transition towards more RES.

3.5. Further research and limitations

While GENeSYS-MOD is already taking into account multiple aspects and challenges of an energy transition, there are some drawbacks. General limitations regarding the model, e.g. temporal resolution, are described in Burandt et al. (2019, 2018) and Bartholdsen et al. (2019). The remainder of this section addresses more specific limitations and further research regarding this study.

A major trait of the model is its large time steps of 5 years with 2015 as its baseyear. Considering the time of completion of this paper, the model's predictions regarding the year 2020 might seem somewhat unrealistic – especially due to the COVID-19 outbreak. Using more recent data in the baseyear assumptions would make results more fitting, but reliable data beyond 2017 is not yet fully available. Furthermore, a crucial factor that needs to be kept in mind is power stability. This is accounted for within the model through a limit of annual expansion of RES relatively to the year prior in order to prevent a shut down of the electricity grid. However, the level of the factor is a controversial topic. In this paper a maximum increase of RES of 6% per year was chosen. Assuming a lower factor, as e.g. Child et al. (2019), could potentially decrease the share of renewables.

Regarding the employment effects, the model is only considering direct jobs in the power sector and is not taking into account indirect jobs at all or fossil fuels other than coal (Rutovitz et al., 2015). Connections between different sectors (indirect and induced jobs) can lead to dynamics in the labour market that should not be underestimated. Therefore, an analysis in all sectors (heat, transportation incl. fuel supply etc.) as well as a comprehensive economy-wide analysis is recommended.

4. Conclusion

This article focuses on two scenarios to (1) evaluate pathways for the South African energy sector and (2) investigate the employment development, focusing on job gains and losses. To do so, the linear bottom-up Global Energy System Model (GENeSYS-MOD) which minimizes the total costs in the power, heat, transport, and industry sectors is used on a provincial level (Löffler et al., 2017; Burandt et al., 2019). Using the employment factor approach by Rutovitz et al. (2015), an employment analysis is added to the model, calculating the direct jobs in the energy sector. While the business as usual (BAU) scenario does not contain any climate constraints, the 2 °C scenario considers a CO_2 budget corresponding to a 2 °C pathway (Hainsch et al., 2018).

The analysis shows that by setting no carbon budget constraints in the BAU scenario, South Africa will not stay within a 2 °C compatible pathway. In 2050, coal still accounts for 20% of the total power generation. Nonetheless, PV and wind dominate the power generation in both scenarios, with higher shares in the 2 °C scenario. This is mainly due to cost competitiveness of renewable energy sources as well as the CO_2 budget constraint in the 2 °C scenario. Furthermore, the model's results display that a power sector relying on 100% RES could be possible by 2045. With higher shares of RES, the power generation across the country decentralizes, leading to an increase in regional production and a more diverse energy mix.

Regarding employment, due to the fast build-up of capacity until 2050, the jobs in RES increases significantly in both scenarios. As a result of the sharper decline in coal demand, coal jobs decrease faster and to a greater extent in the 2 °C scenario. However, most provinces will still benefit from new employment opportunities and the related economic growth. Yet, in the coal intensive province Mpumalan-ga the number of newly created RES jobs is smaller than the jobs lost in the coal sector within the 2 °C scenario. The additional employment sensitivity run for the 2 °C scenario, however, shows that a nearly cost optimal energy system can be created without net job losses even within coal regions. It is, independent from the speed and evolvement of the energy transition, crucial to emphasize the need for alternative job opportunities outside of the energy sector. Possible alternative sectors could include transport, manufacturing, agriculture, and tourism.

Overall, the results show that a largely RES-based energy system can be achieved in South Africa. However, comprehensive plans for job-transfers, support me-chanisms and restructuring are essential and require political will and diverse policies. This includes but is not limited to policies in form of supporting innovation and deployment of RES capacity (e.g. innovation hubs, networks, improvement and expansion of grid and infrastructure, feed-in tariffs) as well as the implementation of financial measures like internalizing external costs and carbon taxes. Regarding the results of the employment analysis, a broad forward-looking orientation is needed to provide holistic adaptive support for workers, communities, and corporations (e.g. wage policies) (Green, 2018). Strategies can include diversification and restructuring to support the development of existing economic activities in various industrial sectors based on local strengths of the affected coal regions (Burton et al., 2019). The retraining of workers by offering educational programs and consultancies supported by regions and communities will play an essential part in the success of the transition. Further research and work on specific measures is recommended to make interventions tangible and practicable.

Author contributions

Conceptualization, J.H., L.K., A.K., N.M., K.L. and P.-Y. O.; methodology, J.H., L.K., A.K., N.M., K.L.; software, K.L.; validation, J.H., N. M., K.L.; formal analysis, J.H., L.K., A.K., N.M., K.L. and P.-Y. O.; data curation, J.H., L.K., A.K., N.M., K.L.; writing—original draft preparation, J.H., L.K., A.K., N.M., K.L., C.H. and P.-Y. O.; writing—review and editing, J.H., L.K., A.K., N.M., K.L., C.H. and P.-Y. O.; visualization, K.L. and N.M.; supervision, K.L., C.H., P.-Y. O.

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Conflicts of interest

The authors declare no conflict of interest.

Declaration of Competing Interest

The authors report no declarations of interest.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at https://doi.org/10.1016/j.envsci.2021.06.001.

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