

Hanto, Jonathan et al.

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

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### A. Detailed model description

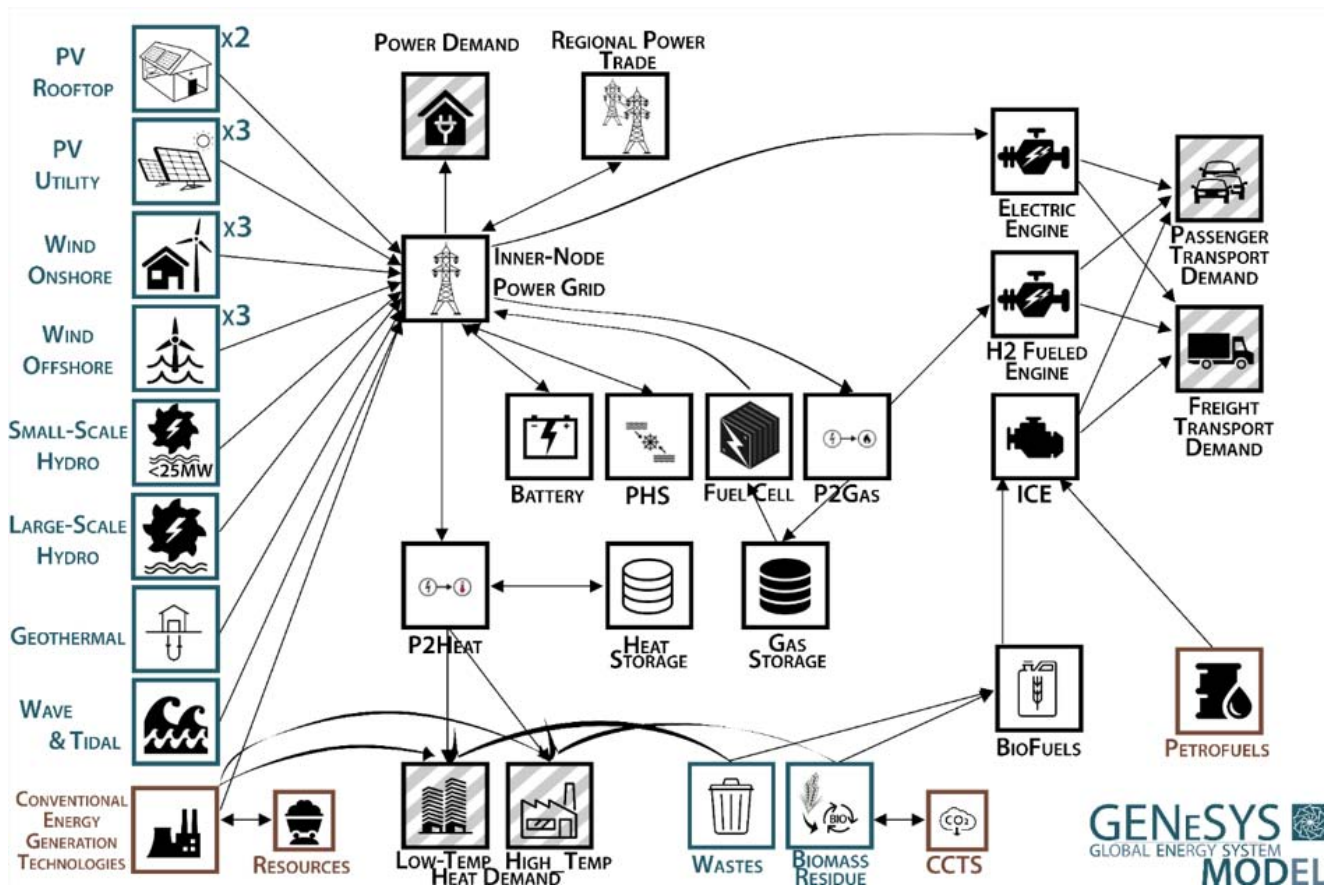


Figure 1: Rough stylization of the interconnections between sectors and demand fuels within GENeSYS-MOD.

The Global Energy System Model (GENeSYS-MOD) is a cost-optimizing linear program, focusing on long-term pathways for the different sectors of the energy system, specifically targeting emission targets, integration of renewables, and sector-coupling. The model minimizes the objective function, which comprises total system costs (encompassing all costs occurring over the modeled time period) (Löffler et al., 2017; Howells et al., 2011).

(Final) Energy demands are given exogenously for each modeled time slice, with the model computing the optimal flows of energy, and resulting needs for capacity additions and storages. Additional demands through sector-coupling are derived endogenously. Constraints, such as energy balances (ensuring all demand is met), maximum capacity additions (e.g. to limit the usable potential of renewables), RES feed-in (e.g. to ensure grid stability), emission budgets (given either yearly or as a total budget over the modeled horizon) are given to ensure proper functionality of the model and yield realistic results.

The model allows for investment into all technologies<sup>1</sup> and acts purely economical when computing the resulting pathways (while staying true to the given constraints). To achieve these results, the model can choose from a plethora of technologies, spanning across multiple sectors, with sector-coupling and storage options being included. Figure 1 shows a stylized version of the interconnections that are implemented in GENeSYS-MOD. Due to computational restrictions, the model does not consider a full hourly time resolution. However, other studies have found that given proper implementation, reduced time series can reach reasonably close results (Burandt et al., 2019; Welsch et al., 2012; Burandt et al., 2018).

The model assumes the role of a social planner with perfect foresight, optimizing the total welfare through cost minimization. All fiscal units are handled in 2015 terms (with amounts in other years being discounted towards the base year). The effects of myopic / limited foresight, as well as the analysis of different discount rate models are planned for further reasearch and might yield even more insight in the possible developments of the energy system.

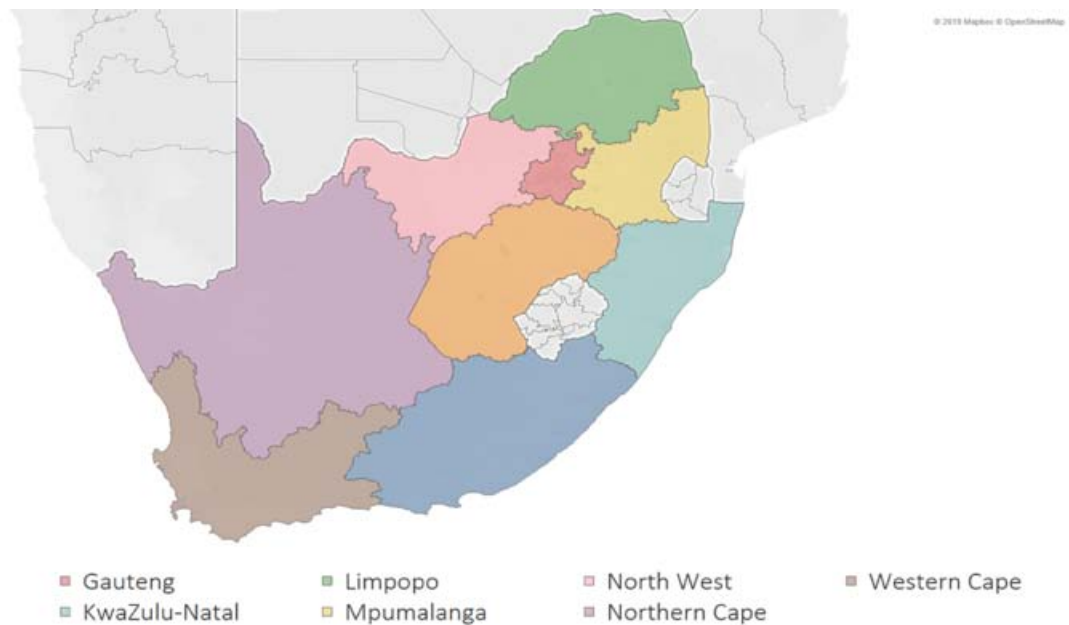
Fore more information on the mathematical side of the model, as well as all changes between model versions, please consult Howells et al. (2011); Löffler et al. (2017); Burandt et al. (2018, 2019).

<sup>1</sup>Except when given fixed, predetermined phase-out dates. For more information, please consult Burandt et al. (2018).

Figure 2 shows the changes to GENeSYS-MOD in it's current version.



**Figure 2:** Technical block structure of GENeSYS-MOD v2.0. The grey boxes in darker shade on the right side represent changes and additions made to previous versions. Based on Howells et al. (2011).



**Figure 3:** Regional Division of South Africa  
Source: Own Illustration

## B. Model input data

The following section provides key data used for the analysis. Table 1 gives an overview of the capital costs for the main technologies, Table 2 contains the sector-specific demand and Table 3 shows the data used for the job calculations in

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

	2015	2017	2020	2025	2030	2035	2040	2045	2050
Utility PV	1000	832	580	466	390	337	300	270	246
Onshore Wind	1250	1210	1150	1060	1000	965	940	915	900
Offshore Wind	3500	3155	2637	2200	1936	1800	1710	1642	1592
Large Hydropower	2200	2200	2200	2200	2200	2200	2200	2200	2200
Coal-fired Thermal Plant	1600	1600	1600	1600	1600	1600	1600	1600	1600
Gas-fired Thermal Plant	650	644	636	621	607	593	579	564	550
Nuclear Power Plant	6000	6000	6000	6000	6000	6000	6000	6000	6000

**Table 1**

Capital Costs of main electricity generating technologies in M€/GW

Source: Based on ETRI (2014); Oyewo et al. (2019); Gerbaulet and Lorenz (2017)

	2015	2017	2020	2025	2030	2035	2040	2045	2050
Power [PJ]	807	841	878	975	1058	1128	1195	1260	1329
Industry Heat (high) [PJ]	381	389	402	418	434	438	441	445	449
Industry Heat (medium) [PJ]	304	310	320	333	346	349	451	354	357
Industry Heat (low) [PJ]	379	387	400	416	432	435	439	442	446
Residential Heat (low) [PJ]	56	61	70	78	86	93	101	108	115
Freight-Mobility [Gtkm]	454	470	494	536	583	633	688	748	813
Passenger-Mobility [Gpkm]	409	423	445	483	525	571	620	674	732

**Table 2**

Sector-specific demand

Source: Based on National Treasury (2003); CSIR (2017); of Energy South Africa (2012); Lombard et al. (2007); Department of Transport (2018); International Energy Agency (2019); IndexMundi (2016); CSIR (2014)

	C&I [Jobs/GW]	Manufacturing [Jobs/GW]	O&M [Jobs/GW]	Fuel supply [Jobs/PJ]
Hardcoal	11200	5400	140	14.97
Gas, Oil, and Diesel	1300	930	140	15.1
Nuclear	11800	1300	600	0.27
Biomass	14000	2900	1500	29.9
Hydro small	15800	10900	4900	-
Hydro large	7400	3500	200	-
Wind onshore	3200	4700	300	-
Wind offshore	8000	15600	200	-
PV	13000	6700	700	-
Geothermal	6800	3900	400	-
Local content for manufacturing [%]	0.35 - 0.75			
Regional adjustment factor	2.15			

**Table 3**

Parameters for the job calculation

Source: Based on Rutovitz (2010); Rutovitz et al. (2015); Ram et al. (2020); Kuntze and Moerenhout (2013); Chamber of Mines South Africa (2018); International Energy Agency (2017)

GENeSYS-MOD.

Jobs	=	Manufacturing	+	C&I	+	O&M	+	Fuel supply + coal mining for all sectors
Manufacturing (jobs/MW)	=	Added capacity	x	Manufacturing employment factor	x	Regional adjustment factor	x	% local manufacturing
C&I (jobs/MW)	=	Added capacity	x	C&I employment factor	x	Regional adjustment factor		
O&M	=	Total installed capacity	x	O&M employment factor	x	Regional adjustment factor		
Fuel supply (nuclear) (jobs/PJ)	=	Electricity generation	x	Fuel employment factor	x	Regional adjustment factor		
Fuel supply (coal, gas, and biomass) (jobs/PJ)	=	Primary energy demand + exports	x	Fuel employment factor	x	Regional adjustment factor		

**Table 4**

Overview of job calculations

Source: Based on Rutovitz et al. (2015)

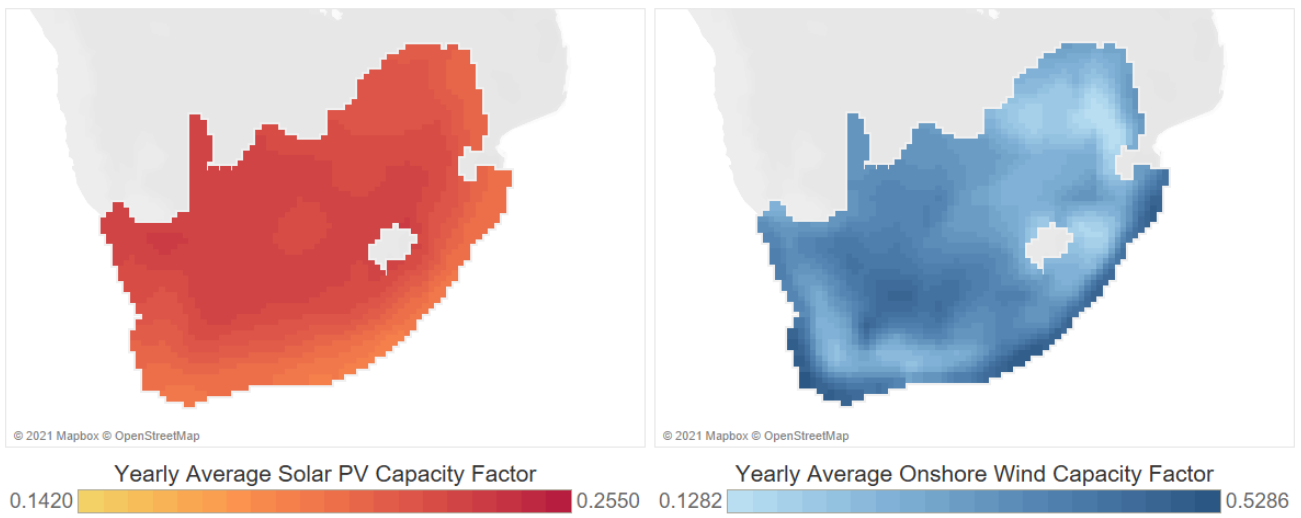
### C. Detailed information on the employment analysis

There are different approaches to quantify the employment impact in the energy transition. The approaches can be primarily distinguished between gross and net analysis. While the first refers to an analysis within a sector or industry (here RE industry), the second is an economic wide analysis (Breitschopf et al., 2012). There are direct jobs accounting for jobs in the RE sector itself as well as indirect jobs, which are jobs in supporting industry, existing in the upstream industry (e.g. steel). Additionally, induced jobs are accounting for jobs beyond the mentioned industries (IRENA, 2013) and are benefiting from the macroeconomic feedbacks, e.g. consumer goods industry (IRENA and Clean Energy Ministerial, 2014). We use the employment factor approach measuring direct jobs as the focus lies on the energy transition, especially on the coal-exit with a just transition.

Table 4 gives an overview of the equations used for the job calculations implemented in GENeSYS-MOD. Nonetheless, there are a couple of limitations to this approach. The employment analysis only focuses on total jobs regardless of their quality in terms of income level, social security status etc.

As important as the installation of a plant is, is its decommissioning and subsequent recycling. Until now, no long-term data is available for the employment effects for renewable energy sources (RES) installations but it seems very likely, that the labor needs are similar in size to the installation phase (IRENA, 2013). Here, it cannot be fully determined yet if a plant is dismantled and repowered after the technical lifespans or enters a second production life with lower efficiency and higher O&M employment due to more maintenance requirements. It is also not clear yet how recycling technologies for energy related technologies will play out in the future. For a scenario with very high resource prices, the employment needs for a recycling industry could be significant and further add to the employment effects in the energy sector itself. In the energy industry, but also other industries, a reduction of lifespans for technical applications can be noted, which further increases the employment effects of installation as well as dismantling and reducing the relatively low share of O&M in the overall equation for employment. Other non-assessed aspects include the employment effects from energy efficiency and the heat sector (Rutovitz et al., 2015).

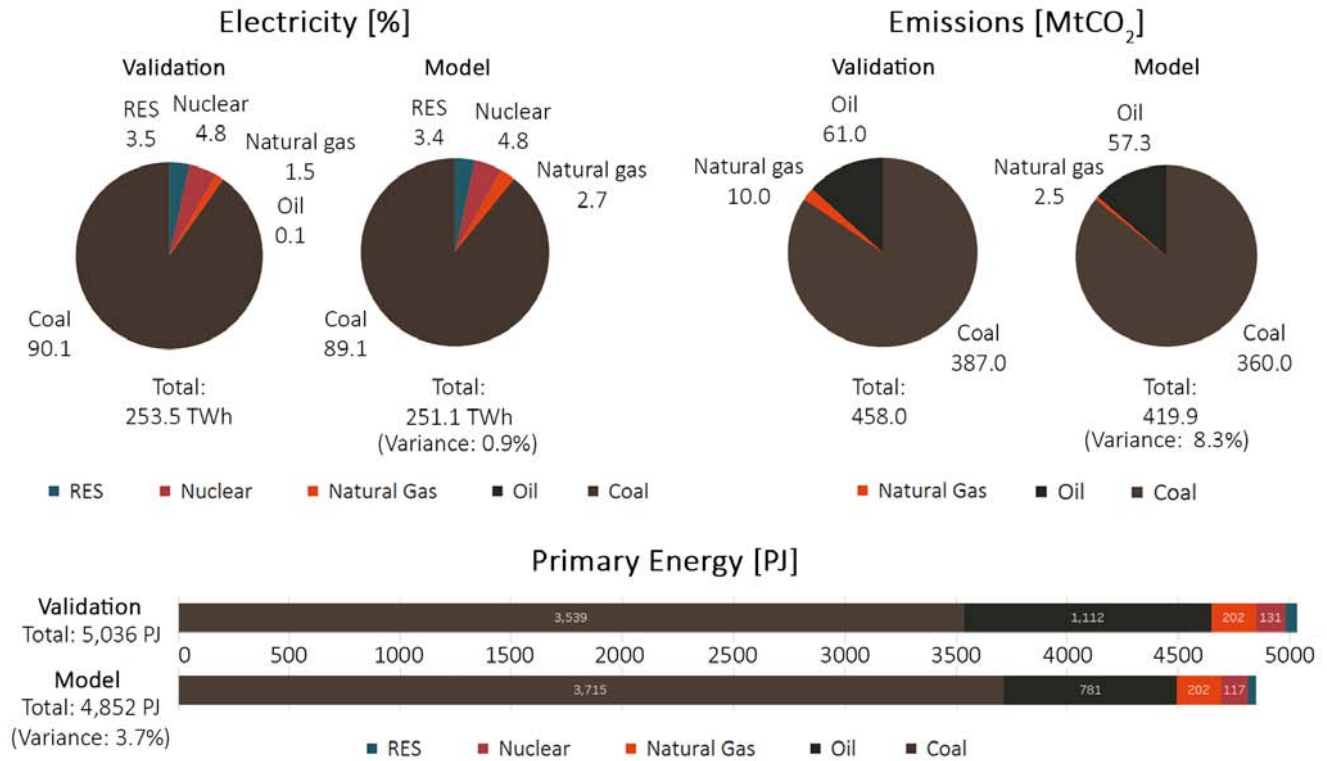
### C.1. Renewable capacity factors



**Figure 4:** Presentation of the yearly average capacity factors for onshore wind and solar PV per data point in a 21x21km grid.  
Source: Own illustration

### D. Model Validation

To prove that the model’s results are valid, a comparison of the base year’s (2015) results with actual data from official international reports (IRENA, 2019; Eskom, 2018; Gilfillan et al., 2019; United Nations Framework Convention on Climate Change, 2019; British Petroleum, 2019; International Energy Agency, 2019) was conducted. In Figure 5 the comparison for electricity, emissions and primary energy is displayed.

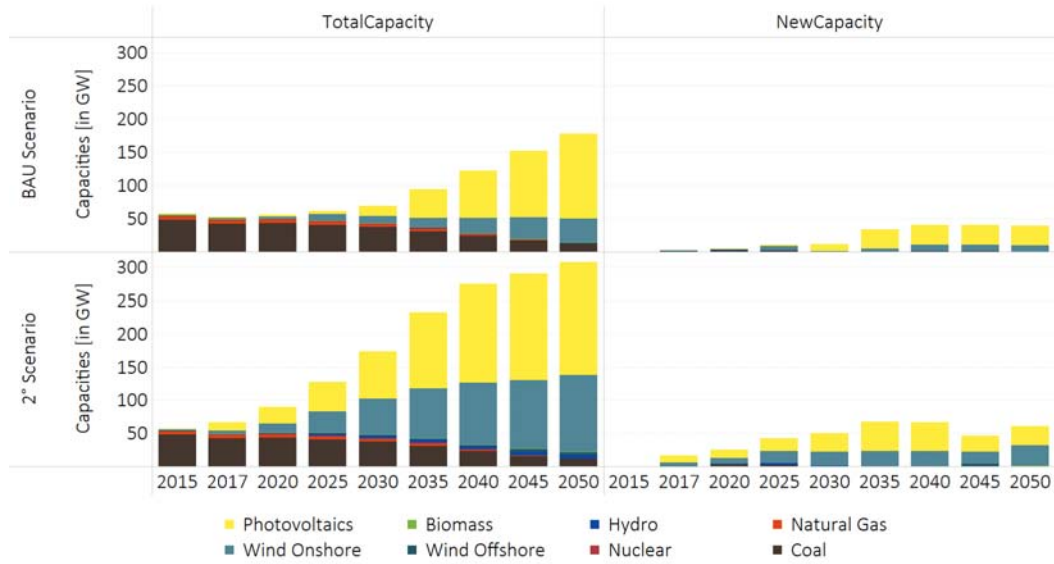


**Figure 5:** Comparison of model results with actual data for 2015. Data for electricity from IRENA (2019) and Eskom (2018); data for emission from Gilfillan et al. (2019), United Nations Framework Convention on Climate Change (2019), and British Petroleum (2019); data for primary energy from International Energy Agency (2019) Source: Own illustration

As can be seen, the variance of the model’s results compared to actual data is reasonably small. The difference in total numbers for emissions and primary energy is about 8% and 4% respectively while that for electricity lies below 1%. Considering that the sources of all model data are official or peer-reviewed academic articles (thus assuming the data to be correct), the model therefore proves to be working accurately.

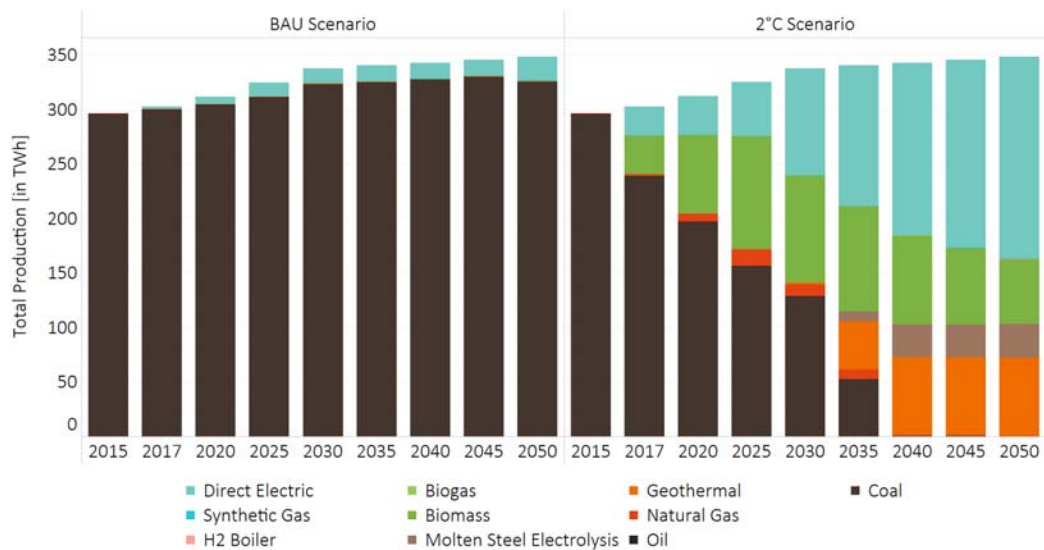
## E. Results

### E.1. Capacity



**Figure 6:** Total and new capacity  
Source: Own illustration

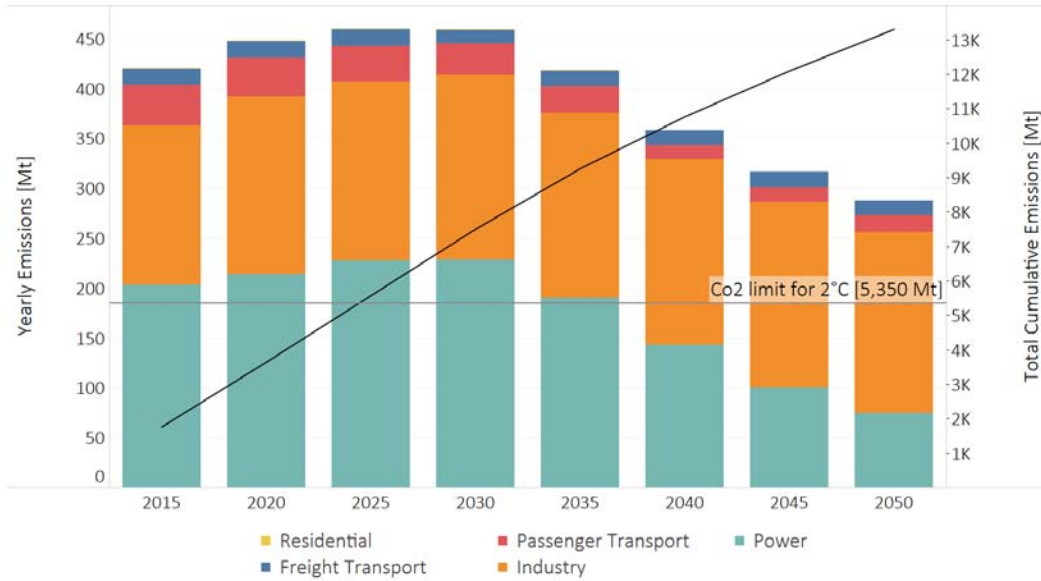
### E.2. Industry Heating Sector



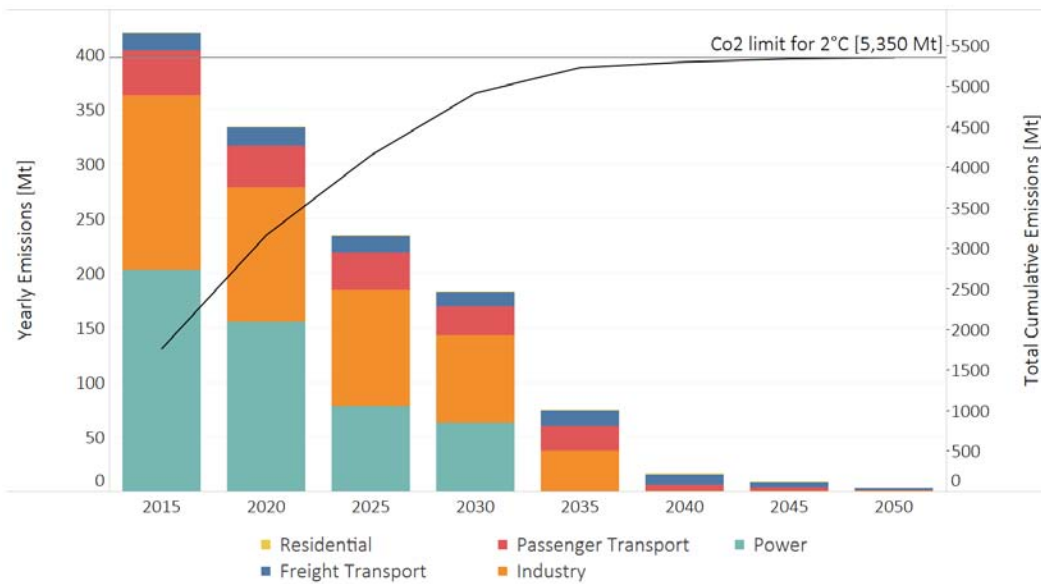
**Figure 7:** Industry Heating Sector South Africa  
Source: Own illustration



### E.3. Emissions

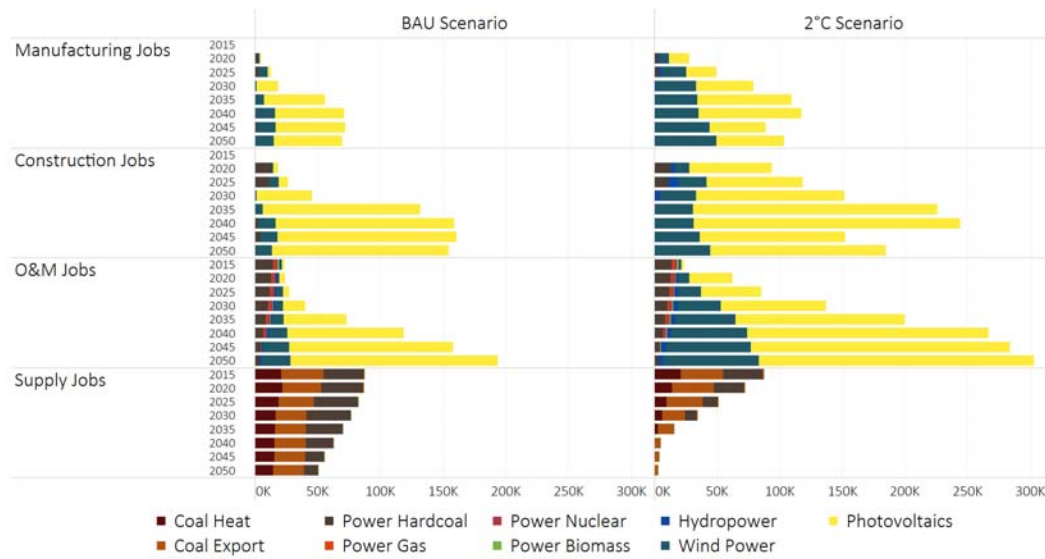


**Figure 8: Emissions BAU Scenario**  
Source: Own illustration



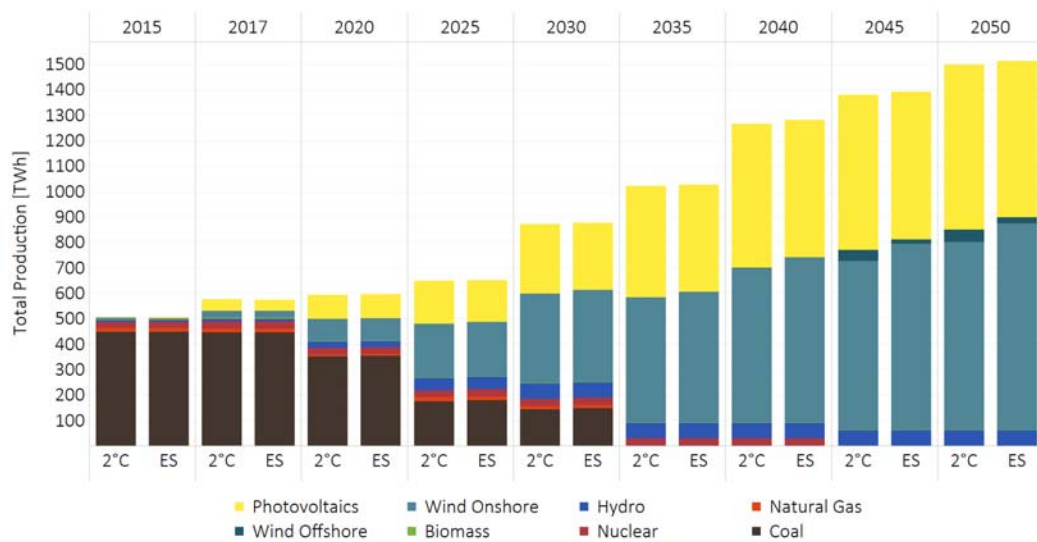
**Figure 9: Emissions 2°C Scenario**  
Source: Own illustration

### E.4. Employment



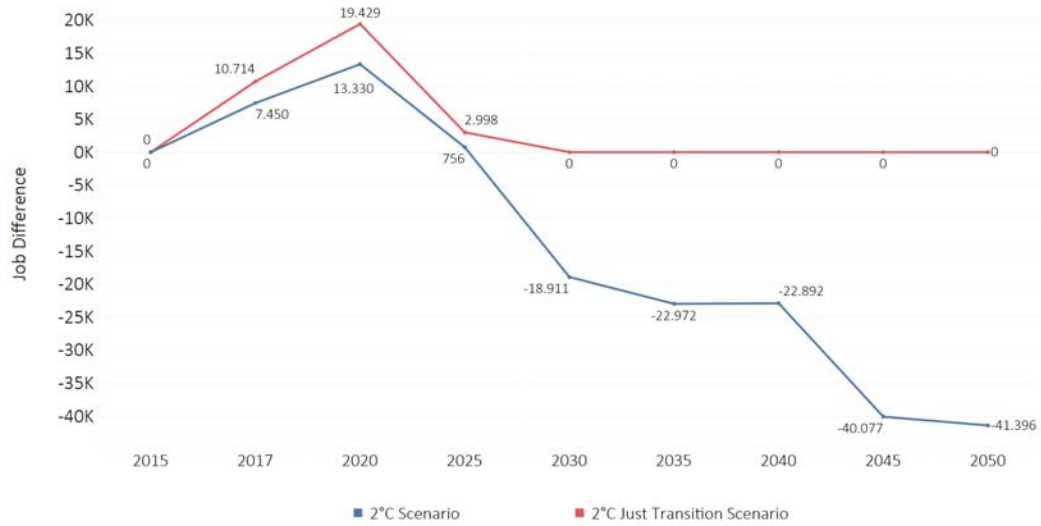
**Figure 10:** Employment effect per job type, year, and fuel in South Africa  
Source: Own illustration

### E.5. Total power production for 2°C scenario and employment sensitivity Sensitivity



**Figure 11:** Total power production for 2°C scenario (2°C) and employment sensitivity (ES) in South Africa  
Source: Own illustration

### E.6. Job difference between 2°C and Sensitivity



**Figure 12:** Development of the number of jobs in the 2°C scenario and the employment sensitivity in Mpumalanga compared to 2015  
Source: Own illustration

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