EP8900 Half paper: Implementation of SSP1 into South Africa MESSAGEix model

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1 Introduction

This paper presents the assignment work conducted as part of the EP8900 PhD-course at NTNU. The chosen assignment was to implement another SSP than SSP2 into the South Africa MESSAGEix model. It was chosen to implement SSP1 which is the "Sustainability" pathway, often named "taking the green road". This SSP was chosen because the main lines of this pathway have relevance to the PhD work running in parallel with this course and the urgency of transforming towards such pathways given the backdrop presented in for instance the latest IPCC reports.

In the subsequent chapters, the following will be presented. First, a short overview of SSP1 and SSP2 is given, highlighting important aspects relevant to the assignment work. Second, the method utilized in the assignment is presented. Third, the results and discussion are given. In this chapter, we also conclude and state the limitations of the assessment. The method and results describe the work documented in the code base that follows this assignment and is published in the course's Github repository. When referring to the code base, we refer to the code in the file South_Africa_SSP1.ipynb. For convenience, the paper uses the term "we" to describe the work conducted even though all work has been carried out by me, Rita Nerland.

2 Theory

In this chapter, we present a short theoretical background on the Shared Socioeconomic Pathways and the MESSAGEix model.

2.1 Shared Socioeconomic Pathways

According to Bauer et al. (2017), the SSPs are intended to serve as reference scenarios for various assessments in the area of climate change challenges, as well as broader sustainability issues. They further elaborate that the SSPs complement the Representative Concentration Pathways (RCPs), by adding the underlying socio-economic narratives and quantitative pathways consistent with the challenges to mitigation and adaptation. It is five SSPs, differing along two axes, namely the challenges to adaption and mitigation to climate change (Riahi et al., 2017).

The SSP1 is the sustainability pathway, commonly described as "taking the green road", with low challenges to mitigation and adaption to climate change. The narrative for this pathway is according to Riahi et al. (2017): "The world shifts gradually, but pervasively, toward a more sustainable path, emphasizing more inclusive development that respects perceived environmental boundaries. Management of the global commons slowly improves, educational and health investments accelerate the demographic transition, and the emphasis on economic growth shifts toward a broader emphasis on human well-being. Driven by an increasing commitment to achieving development goals, inequality is reduced both across and within countries. Consumption is oriented toward low material growth and lower resource and energy intensity." (Riahi et al., 2017, p. 157). SSP2 is a pathway with some similarities with SSP1, but the two pathways have still some fundamental differences. SSP2 is the middle of the road scenario with medium challenges to mitigation and adoption to climate change. The narrative for this pathway is according to Riahi et al. (2017): "The world follows a path in which social, economic, and technological trends do not shift markedly from historical patterns. Development and income growth proceeds unevenly, with some countries making relatively good progress while others fall short of expectations. Global and national institutions work toward but make slow progress in achieving sustainable development goals. Environmental systems experience degradation, although there are some improvements and overall the intensity of resource and energy use declines. Global population growth is moderate and levels off in the second half of the century. Income inequality persists or improves only slowly and challenges to reducing vulnerability to societal and environmental changes remain." (Riahi et al., 2017, p. 157).

2.2 MESSAGEix

MESSAGE is an abbreviation for "Model for Energy Supply System Alternatives and their General Environmental Impacts" and is one of the four Integrated Assessment Models (IAMs) used for preparing the Representative Concentration Pathways (RCPs) (EP8900 Presentation, 2022). The model is developed by the International Institute for Applied Systems Analysis (IIASA). "MESSAGEix represents the core of the IIASA IAM framework and its main task is to optimize the energy system so that it can satisfy specified energy demand at the lowest cost" (IAMC, 2020). In other words, MESSAGEix is an optimization model that minimizes the total system costs under a set of constraints. The model is dependent on a set of input parameters and produces a set of decision variables. The unit of the value of the objective function is given in million US dollars (MUSD).

In this assignment, we use a country-level version of the MESSAGEix model, for South Africa. This model was originally developed through the work of Orthofer et al. (2019), which assessed the role shale gas could play in solving South Africa's so-called energy trilemma (see Orthofer et al. (2019) for more information). As stated by Orthofer et al. (2019), their analysis focuses on the medium-term outlook until 2050, and that the underlying model extends to 2070 to avoid end-of-time-horizon effects, which might otherwise bias the numerical results (Orthofer et al., 2019). This is also the time horizon of our assessment when looking into the SSP1 pathway.

3 Methods

The assignment was conducted on a step-by-step basis, where the selected parameters of the South Africa model was assessed one by one. Even though SSP1 and SSP2 are quite similar in some areas, as for instance technological progress and macro-economy for conventional hydrocarbons (Riahi et al., 2017, Table A.2), their fundamental differences make changing the values of numerous parameters in the MESSAGEix model, logical. Doing so is however not of scope in this assignment. We chose to focus on a few of the most relevant parameters that were likely to change when moving from a SSP2 to a SSP1 pathway. In the following sections, we present the procedure for each of the parameters that we changed. Lastly, we present the methodology used for post-processing and plotting the results.

3.1 Demand Parameter

We started by assessing the demand parameter. We downloaded data from the SSP database, which holds projected population and GDP data for South Africa. We chose the data from IIASA for both the population and GDP. The demand in MESSAGEix is represented in GW-years (GWa) for the various commodities. The baseline South Africa model follows the SSP2 pathway. Estimating the SSP1 demand was done in a "trial and error" manner, using the population and GDP data for SSP1 and SSP2 in order to calculate different metrics. We calculated the demand per population, per GDP, and per GDP per population for SSP2 and used this metric and the corresponding SSP1 data to re-scale the demand to an estimated SSP1 pathway. These results are summarized in Figure 1 on the next page.

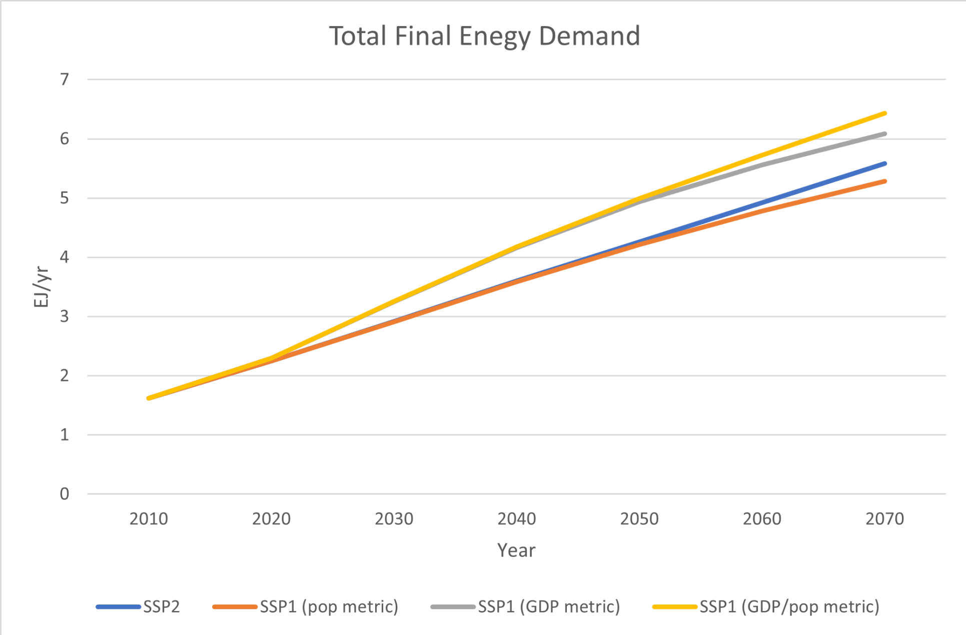

Figure 1: Demand for various re-scaling methods. SSP2 is given, the SSP1 variants are estimated with the use of different metrics.

Further, we used the work of Riahi et al. (2017) to assess which of these paths were most likely. From figure 3c (Riahi et al., 2017, p. 159) we found that the total final energy demand at the global level for SSP1 is below the total final energy demand for SSP2 from approximately 2020 and throughout the century. This is also in line with the energy tables in their appendices which state a modest service demand for SSP1 and a medium service demand for SSP2. Consequentially, we settled on using the SSP1 (pop metric) as visualized in Figure 1. We imported the population data for SSP1 and SSP2 as lists in our code base and used these lists to adjust the demand for all the commodities included in the model. These calculations are performed in code block 8 and the adjustment of the demand is performed in code block 9.

3.2 Cost Parameters

We know that the energy mix and the carbon intensity for technologies differ between SSP1 and SSP2. The narratives do not present detailed information on this, but some previous studies have demonstrated the projected distribution based on their scenario simulations. van Vuuren et al. (2017) projected the energy mix for the global and regional levels. Their global findings are that: "In terms of energy supply, the SSP1 scenario is characterized by a transition from a fossil-fuel dominated system (nearly 90% of energy supply in 2010) towards an energy system in which renewable energy plays a key role. This transition needs time as a result of existing infrastructure and the related competitive position of fossil fuels (Fig. 3). Despite the slow changes, even before 2050 oil use is substantially reduced and coal use increases only slightly. Natural gas use in contrast is projected to grow significantly as a result of relatively low prices and the better environmental performance compared to other fossil fuels. By 2100 in SSP1, total fossil fuel consumption is substantially below today's level of fossil fuel use, while oil use is nearly phased out (see transport system)." (van Vuuren et al., 2017, p.242).

The main levers for adjusting energy mix and carbon intensity in MESSAGEix are by changing the cost parameters for specific technologies, as well as constraining their deployment. In MESSAGEix, the cost parameters are divided into three parts: Investment costs, fixed costs, and variable costs. The cost parameters are given at the technology level. The specific built-up of the cost parameters vary, depending on how the costs are distributed across time (yeat_vtg and year_act). According to the documentation, fixed and variable cost parameters and technical specifications are indexed over both the year of construction (vintage) and the year of operation (actual). And further that this allows to represent changing technology characteristics depending on the age of the plant.

We estimated the costs for the SSP1 pathway by using the given SSP2 values as a reference and furthermore interpreting the diagrams of van Vuuren et al. (2017). Since the costs are attributed to various technologies and the technologies can have a primary, secondary, final, useful, resource, or renewable, "level", and are also divided according to sector - we used the diagram(s) that were most fit for the purpose for each case. The scaling procedure was thus heavily dependent on our interpretations of the diagrams of van Vuuren et al. (2017) and how we grouped the various technologies into categories. For readability, we have simply included the plots as given in van Vuuren et al. (2017) in the appendices of this paper (see Figure 3, Figure 4 and Figure 5).

The estimation was done by introducing scaling factors for the various affected technologies. In cases where several technologies were affected by the same scaling factor, we made technology sets to make the calculation more compact. In total, we introduced 12 scaling factors. These were used to programmatically adjust the affected cost components in the SSP1 pathway. The scaling factors were constructed as lists where one factor was assigned for each year from 2030 to 2070. For example, we found through Figure 3 (van Vuuren et al., 2017) that the demand for primary coal is slightly higher for SSP2 than SSP1 in 2050 and significantly higher in 2100. This finding implied that the coal_extr cost was multiplied by the factor we named "coal_factor" which had the following values: [1.02, 1.02, 1.02, 1.04, 1.04]. Less energy demand is thus integrated by scaling up the costs of the given technology and vice versa. The scaling factor lists are constructed in code block 11. The comments in this block also provide reasoning for how the various factors were estimated.

We chose to simplify the estimation of the cost parameters in several ways. First, we constructed scaling factors for each set of technologies. The technology sets were grouped according to the technology categories in the energy consumption curves as given in the literature. Second, we assumed that all cost components of a technology had the same scaling factor. This is certainly an assumption that might be wrong, especially for labor-intensive technologies. Third, we chose to disregard all import and export components of the technologies, as well as the cost components that had zero values, i.e. keep them "as is" in the SSP2 baseline scenario.

Besides this, the following technologies were kept "as is" since the scope of this assignment made it impossible to assess the development of all technologies: The bio_istig, bio_extr, biomass_i foil_ppl, foil_i, biomass_t_d, gas_bal, gas_bio, gas_t_d, loil_t_d, all "meth" (methanol) technologies, oil_bal, and ref_hil.

The bullet points that follows provides a short sum-up of the reasoning undertaken for the various technologies:

- One factor list for all assessed coal technologies due to a similar trend in all figures (primary, secondary, and industry final).
- elec_trp was kept "as is" since the "Transport Final Energy" diagram in Figure 5 does not display any trend (not much difference in the size of the blue "Elec" area between SSP1 and SSP2).
- gas_extr and shale_extr were kept "as is" since Figure 3 does not display any trend (not much difference in the size of the blue "Gas" area between SSP1 and SSP2).
- hydro_ppl were kept "as is" since Figure 3 does not display any trend (not much difference in the size of the dark blue "Hydro" area between SSP1 and SSP2).
- loil_fs and loil_i were kept "as is" since the Figure 5, diagram "Industry Final Energy" does not display any trend (not much difference in the size of the red "Oil" area between SSP1 and SSP2). Assumes lightoil is included in the oil category in Figure 5.
- loil_ppl were kept "as is" since Figure 4, does not have an oil category. Assumes it is included in "Other", which has a negligible change between SSP1 and SSP2.
- loil_rc were kept "as is" since the Figure 5, diagram "Residential Final Energy" does not display any trend (not much difference in the size of the purple "Heat" area between SSP1 and SSP2).
- sp_el_RC were kept "as is" since the Figure 5, diagram "Residential Final Energy" does not display any trend (not much difference in the size of the dark blue "Elec" area between SSP1 and SSP2).

3.3 Bound Activity Up parameter

We also adjusted the bound activity up parameter, by using the same kind of reasoning as with the cost parameters. In this case, we also only adjusted the values that had values in the baseline SSP2 scenario, meaning that we did not introduce any new activity boundary values. Many of the existing boundaries had 2020 as year_act. These boundaries were not changed.

We went through the existing values and implemented new scaling factors for the relevant technologies. We used the same reasoning as for the corresponding cost factors but changed the influence so that a decrease in cost was transferred to an increase in the bound activity up.

3.4 Interest Rate

The interest rate parameter in MESSAGEix is the economy-wide interest rate. This means that this is a parameter that affects all technologies. Reducing the interest rate parameter work in favor of capital intensive technologies, such as solar and nuclear, and similarly in disfavor of technologies that are less capital dependent, such as coal. We reduced the interest rate by 1 percent point from 0.05 to 0.04 from the years 2030 to 2070. This is done in code block 33.

3.5 Introducing Emission Bound Scenario

After having adjusted the interest rate parameter, we committed the SSP1 scenario to the platform and solved it (code block 36 and 37). Now, we wanted to tweak the scenario to find how the various variables changed when we implemented an emission bound on CO2. We cloned the "SSP1_Scenario" to a new "SSP1_BE_Scenario" (code block 38 and 39) and introduced a value to the "bound_emission" parameter. We used South Africas' National Determined Contribution (NDC) to determine the value. Climate Action Tracker (n.d.) states that South Africa's updated NDC submitted in 2021 targets an absolute emissions level in the range of 350–420 MtCO2e including LULUCF for 2030. Based on this, we chose to introduce a cumulative emission bound on 400 MtCO2 for CO2. We introduced an emission bound on CO2 because the model only produces one other GHG gas emission, CH4, which we found to have a negligible value compared to CO2.

3.6 Methodology for post-processing

After the two SSP1 variants were committed and solved, we started post-processing the data. We started by printing values for the objective function for the three scenarios. After this, we implemented "message_ix_reporting" to our code environment. According to the docs, the reporting module refers to calculations and other post-processing performed after a scenario has been solved by the associated optimization model. We used the report module to plot our results in stacked bar charts. This was done by introducing "quantities" as defined in the docs. We produced plots for the emissions, the extraction, the new capacity, and the activity, for both the SSP1 and SSP1 BE scenario, in addition to the baseline. The plots were inspected visually and compared. It is also worth mentioning that several of the plots were produced while using some highly selective filters with respect to the years and technologies included.

In order to do some more hands-on visual comparison, we transferred some of the output values to MS Excel. This was done to produce diagrams where both the SSP1 variants and the baseline scenario were included simultaneously.

4 Results and Discussion

In this chapter, we discuss some of the results produced by the model. To narrow down the scope of this paper, we chose to assess some selected output variables; objective function, emissions, extraction, new capacity, and activity.

4.1 Objective function

The value for the objective function for the various scenarios and the baseline scenario is given in Table 1 on the next page, along with the percentage increase for the two assessed SSP1 scenarios compared to baseline.

Table 1: Table of objective function values and percentage increase compared to baseline

	Baseline	**SSP1**	**SSP1 BE**
System costs	63014.57 MUSD	68915.3 MUSD	71705.52 MUSD
Percentage change	-	9 %	14 %

As stated in the introduction, MESSAGEix's objective function minimizes the total system costs under a set of constraints. We observe that the adjustment of demand, cost parameters, bound activity up, and interest rate leads to an approximately nine percent increase in the objective function value. Adding an emission bound to the model increases the costs by five percentage points more, to fourteen percent. These are reasonable results, given that the GDP increases more in SSP1 than in SSP2 (Riahi et al., 2017, Fig 2, p.158), thus the total system activity is expected to increase, which again is expected to increase the system costs. Higher systems costs are expected in a green growth paradigm.

4.2 Emissions

One of the most interesting variables to discuss for the scope of this assignment are emissions. We implemented the reporting module of MESSAGEix and produced stacked bar charts for the scenarios. These plots are produced in the code base (code block 51 to 53). Figure 2 below provides a snapshot picture of the 2050 emissions for the baseline and the two SSP1 scenario variants.

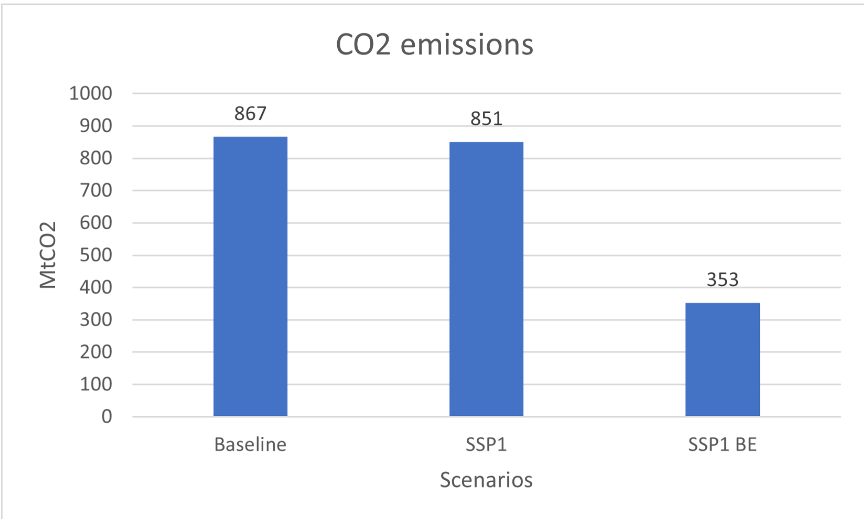

Figure 2: Emissions for the various scenarios in 2050

As expected, the emissions for the SSP1 BE scenario is significantly lower than for the baseline and the SSP1 scenario because of the emission bound at 400 MtCO2 with a cumulative distribution (average at 400 MtCO2 from 2020-2070). However, we observe that the model has produced only small reductions (down approx 16 MtCO2) for the SSP1 without emission bound compared to baseline. We could expect a higher reduction given the narrative of SSP1 and the global findings illustrated in (Riahi et al., 2017, Fig. 5, p.162). This suggests that the adjustment of the cost parameters might have been too conservative. Increasing the scaling factors, i.e implementing an even higher penalty for the fossil technologies and more benefits for renewables, introducing bounds for additional technologies, and adjusting other activity-related parameters are measures that could be implemented in the SSP1 scenario to reduce the emissions even more. It is however important to note that geographical differences are expected and that the global CO2 emission plot should be interpreted with caution when assessing country-level emissions.

When looking at the detailed plots for the scenarios we observe that the emissions increase steadily from 2020 to 2070 in the baseline and the SSP1 scenario. In the SSP1 BE scenario the emissions increases slightly from 2020 to 2030 and then goes rapidly down from almost 500 MtCO2 in 2040 to approximately 350 MtCO2 in 2050.

4.3 Comments on some additional variables

We also assessed the capacity, extraction, and activity variables. Plots for these are produced in the code base and are not reproduced here.

The extraction variable reflects the extraction of non-renewable/exhaustible resources from reserves. We found that the extraction variable is dominated by coal extraction for all the scenarios. In the extraction plots without filters, produced in code block 57-59, we found that the coal extraction increases throughout the assessment period for the baseline and SSP1 scenario, while it more or less stabilizes around 175 GW for the SSP1 BE scenario.

In order to assess the extraction from the other resources (crudeoil, gas, and shalegas), we produced extraction plots without coal (code block 60-62). These plots illustrate that the extraction of other resources are in the range of less than one GW, and that crudeoil is the resource with the highest extraction after coal, for all three scenarios.

Another interesting variable to assess was the new capacity. This variable quantifies the newly installed capacity (yearly average over period duration) for the various technologies. When assessing this variable, we chose to introduce filters where all the renewable technologies were included. We found that the wind power plant technology dominates the new capacity for both the baseline and the SSP1 scenario, with some differences among the decades. Solar thermal power plant is the renewable technology with the most newly installed capacity in 2020 for both, while wind power plant dominates in the subsequent years. The plots for the baseline and the SSP1 scenario also illustrate that the new installed capacity is at its peak in 2050 at approximately 3 GWa. After 2050 the new installed capacity goes rapidly down for the baseline scenario, while it almost holds its max value through 2060 for the SSP1 scenario before it decreases rapidly throughout the last decade included in the model. Again, we find that the SSP1 BE scenario produces dissimilar results to the two other scenarios. Here, we find higher shares of solar and an increasing trend from 2020 to 2070, from less than 1 GWa in total to over 8 GWa in total in 2070.

Lastly, we produced plots for the activity variable. This variable produces the number of GWa for each technology, also taking the vintage year into account. To make the plots readable, we chose to introduce filters for technologies, vintage year, and actual year. In selecting technologies we found, not surprisingly that coal extraction and coal_bal (link technology to stabilize coal production) dominated the activity when not including any technology filter. We chose to include the same renewable technologies as we did for the new capacity plots, as well as some of the coal technologies with less activity. Not surprisingly we find a correlation between the new capacity plots and the activity plots, where the baseline scenario gets a higher share of wind for the activity in 2050 that has 2040 in vintage year (correlates towards relatively higher new capacity in 2040), and the SSP1 scenario gets a higher share of wind in 2050 that has yv=2050. The activity plots of the baseline and SSP1 scenarios illustrate that the selected coal technologies dominate the total activity in 2050.

The SSP1 BE activity plot is more colorful, meaning that we now see several technologies with higher activity levels. Now, solar makes its entrance with over 20 GWa in 2050. The coal technologies are evident in these scenarios as well, but the renewables have clearly higher activity levels than the baseline and SSP scenario in 2050.

4.4 Sum-up

First of all, the work conducted in this assignment provides insights on how one can "tweak" parameters of the MESSAGEix South Africa model to assess different SSPs. Our results suggest that moving from a SSP2 pathway towards a SSP1 pathway results in less emissions, less extraction of fossil fuels, and higher new capacity and activity of renewable technologies. We have also found that introducing an emission bound compatible with the NDC of South Africa provides a more efficient shift towards a green society and that the adjustment of cost parameters, the bound activity up, and the interest rate have less effect. This also suggests that the scaling factors that were implemented were reliant on current economical trends and thinking, with regard to marginal costs in the energy sector. In other words, "scaling up" these factors would be likely to produce a SSP1 scenario more in alignment with the narratives.

We also found that introducing an emission bound to the constructed SSP1 scenario is an effective way to utilize the MESSAGEix model features and that introducing a strict bound at 400 MtCO2 only increased the system costs by an additional five percentage points. Without going into the details of the macroeconomic computations in the underlying model, this seems like an efficient way to include a SSP1 pathway into the model, and more importantly, as a policy measure in the real-world context. The model does, however, not tell us anything about how such an emission bound could be introduced in practice.

This scenario assessment holds several limitations. First of all, the estimation of new parameter values was highly experimental, which could produce a SSP1 pathway not in sufficient alignment with the narratives it is trying to reflect. Second, we narrowed down the scope of the assessment to only tweak the demand parameter, the cost parameters, the bound activity up parameter, and the interest rate parameter. As mentioned earlier, the inherent attributes of the SSP pathways and the fundamental differences between SSP1 and SSP2 could make reason for adjusting numerous parameters. Third, not all technologies were adjusted for all technologies, and technologies that had zero values were disregarded from the adjustment exercise. In sum, all of these simplifications could lead to both limitations in the results, as well as bias (because of the scaling procedure, relying on global plots for some of the technologies, as well as the subjective evaluation of the modeler).

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A Energy Figures

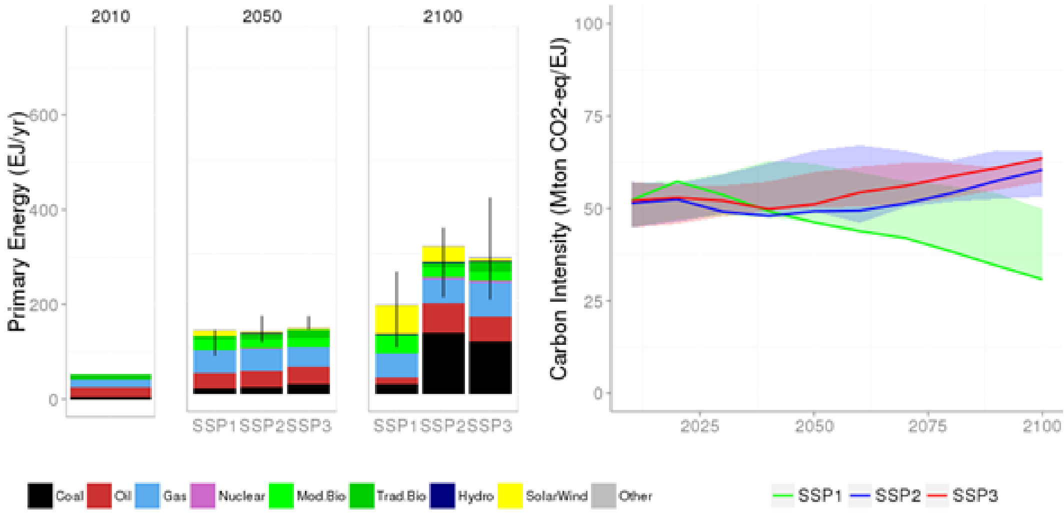

Figure 3: Primary energy and carbon intensity for Middle East and Africa, as illustrated in the appendices of van Vuuren et al. (2017). “Primary energy use per energy carrier and CO2 emissions per unit of primary energy. The vertical lines and shaded area indicate the range of results of the full set of IAM scenarios for the specific SSP (see references in Section 2)” (van Vuuren et al., 2017).

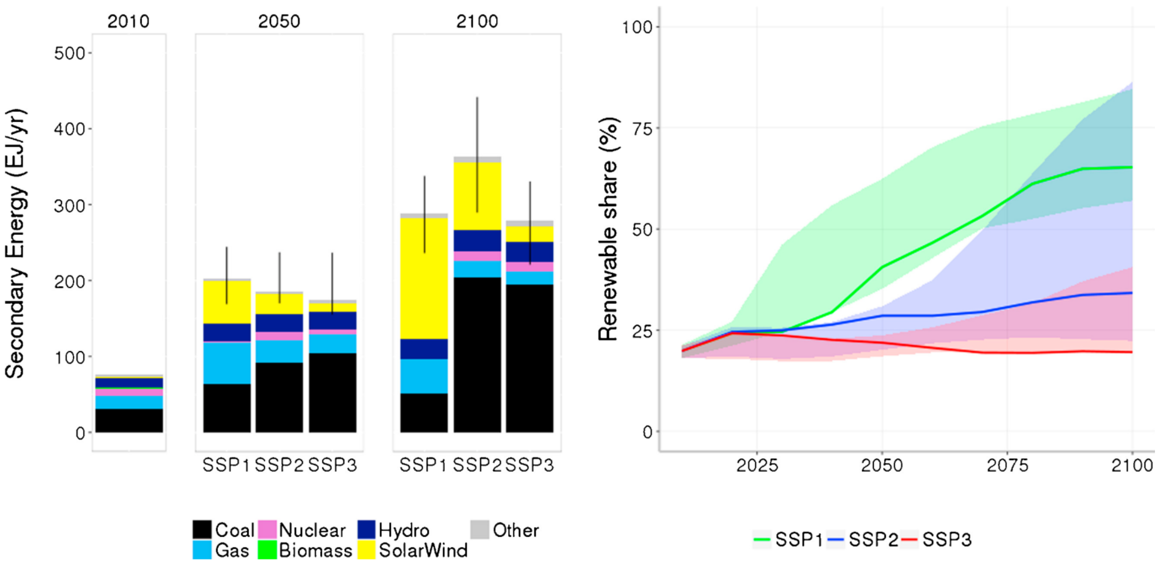

Figure 4: Secondary energy and renewable share at the global level, as illustrated in van Vuuren et al. (2017). “Fig. 4. Power system development and renewable share. The vertical lines and shaded area indicate the range of results of the full set of IAM scenarios for the specific SSP (see references in Section 2)” (van Vuuren et al., 2017).

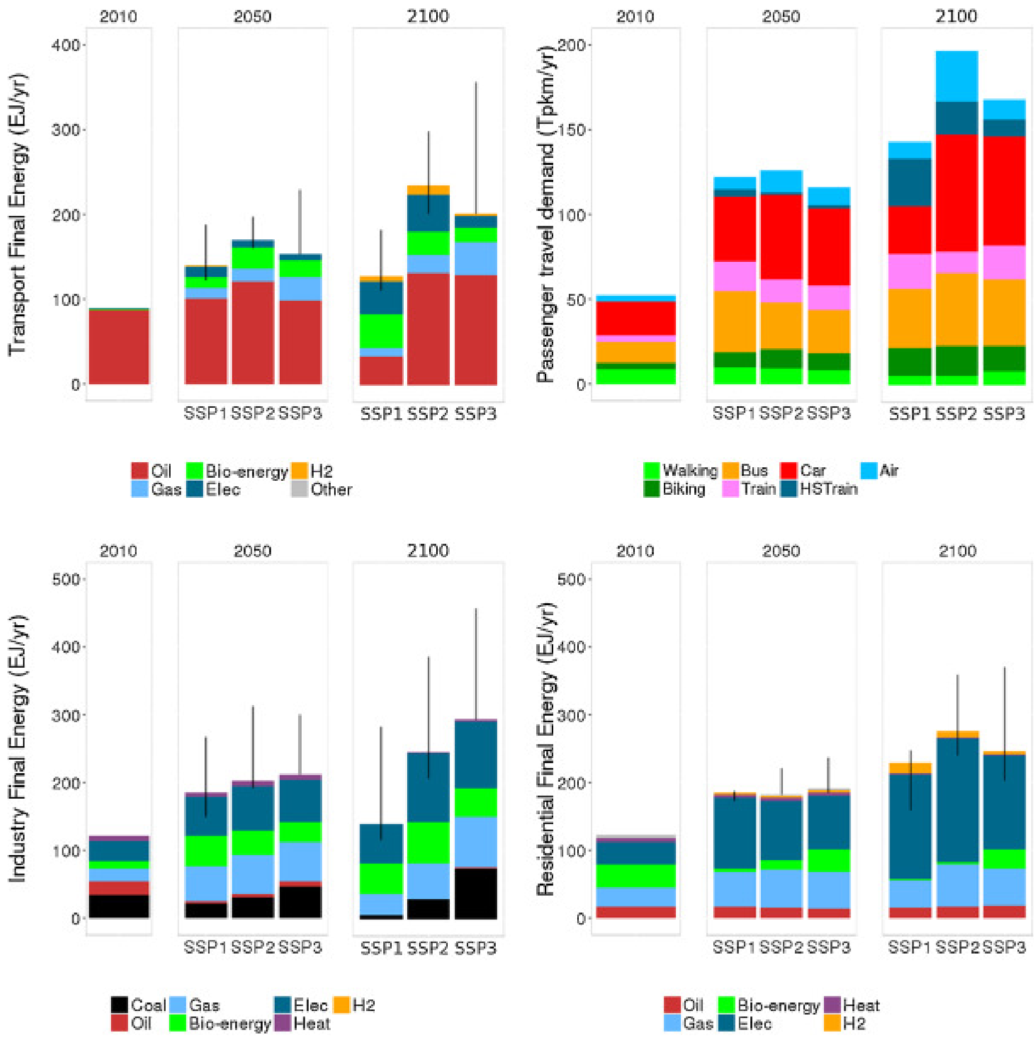

Figure 5: Sectoral energy demand at the global level, as illustrated in van Vuuren et al. (2017). "Development of sectoral energy demand. Transport final energy demand, transport activity levels, industrial and residential final energy use (in the different panels). The vertical lines indicate the range of results of the full set of IAM scenarios for the specific SSP (see references in Section 2). (HSTrain = high-speed train; elec = electricity)" (van Vuuren et al., 2017).

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