International Journal of Electrical, Electronic and Communication Sciences
ISSN: 2517-9438
Vol:14, No:10, 2020

Integrated Modeling of Transformation of Electricity and Transportation Sectors: A Case Study of Australia

T. Aboumahboub, R. Brecha, H. B. Shrestha, U. F. Hutfilter, A. Geiges, W. Hare, M. Schaeffer, L. Welder, M. Gidden

***Abstract*—**The proposed stringent mitigation targets require an immediate start for a drastic transformation of the whole energy system. The current Australian energy system is mainly centralized and fossil fuel-based in most states with coal and gas-fired plants dominating the total produced electricity over the recent past. On the other hand, the country is characterized by a huge, untapped renewable potential, where wind and solar energy could play a key role in the decarbonization of the Australia's future energy system. However, integrating high shares of such variable renewable energy sources (VRES) challenges the power system considerably due to their temporal fluctuations and geographical dispersion. This raises the concerns about flexibility gap in the system to ensure the security of supply with increasing shares of such intermittent sources. One main flexibility dimension to facilitate system integration of high shares of VRES is to increase the cross-sectoral integration through coupling of electricity to other energy sectors alongside the decarbonization of the power sector and reinforcement of the transmission grid. This paper applies a multi-sectoral energy system optimization model for Australia. We investigate the cost-optimal configuration of a renewable-based Australian energy system and its transformation pathway in line with the ambitious range of proposed climate change mitigation targets. We particularly analyse the implications of linking the electricity and transport sectors in a prospective, highly renewable Australian energy system.

***Keywords*—**Decarbonization, energy system modeling, sector coupling, variable renewable energies.

I. Introduction

To achieve the proposed climate change mitigation targets, there is necessity for a drastic transformation of today's energy system. Increasing penetration of renewable energies, in particular solar and wind energy, plays a crucial role in such a low-carbon transformation. Large-scale integration of intermittent energy sources requires extensive adaptation of energy system to ensure the security of supply. Exploitation of the existing potential for cross-sectoral linkages as well as extension of cross-border power transmission and storage capacities plays an important role to fill the system's flexibility gap while increasing the share of VRES.

Australia's current power system is dominated by fossil fuels in most states, while 80% of Australia's total produced power was generated by coal and gas-fired plants in 2018 [1]. On the other hand, the country is characterized by a vast, untapped potential for exploitation of renewables, in particular solar and wind energy [2], [3]. The states of New South Wales, Queensland, Victoria, South Australia, and Tasmania are interconnected within the National Electricity Market (NEM), whereas the states of Western Australia and Northern Territory have power systems isolated from the rest of the country.

To perform a systematic analysis of the Australia's energy system-wide implications of renewable integration and further imposed boundary conditions such as emission constraints, we developed the multi-sectoral Australian Energy Modeling System (AUSeMOSYS). Linking the power and transport sectors as a crucial part of the mitigation efforts to reduce the energy system CO_2 emissions is an ongoing research topic and our particular focus throughout this paper. Linking the power and transport sectors is realized on one hand through direct use of electricity in battery electric vehicles. This is further complemented by indirect application of renewable power through use of hydrogen, produced via electrolysis as the so-called "power-to-gas" approach, in fuel-cell electric vehicles.

Applying the AUSeMOSYS model, we calculate the cost-optimal configuration of a fully decarbonized Australian energy system and its development pathway over a time horizon until 2050, incorporating electricity and transportation sectors. The application of battery electric vehicles (BEVs), fuel-cell electric vehicles (FCEVs) as well as extension of power transmission grid and storage capacities significantly contributes to the smoothening of the temporal variability of wind and solar and reduces the total system costs. We compare the optimal configuration of a prospective Australian energy system by varying the possibilities for cross-sectoral integration as well as transmission grid extensions and the implied emission reduction targets.

This paper is structured as follows: Section II describes the methodology and the model's characteristics. Section III elaborates on the input assumptions and data sources applied in this study. The scenario analysis and discussion of model results are presented in Section IV. Section V summarizes the paper and draws conclusions.

T. Aboumahboub is with Climate Analytics GmbH, Ritter Str.3, 10969 Berlin (corresponding author, phone: +49(0)30-259-229520; e-mail: tina.aboumahboub@climateanalytics.org).

R. Brecha is with University of Dayton, Department of Physics, Renewable and Clean Energy Program, Hanley Sustainability Institute. He is also with Climate Analytics GmbH, Ritter Str.3, 10969 Berlin (e-mail: robert.brecha@climateanalytics.org).

H. Bir Shrestha, U. Fuentes Hutfilter, A. Geiges, W. Hare, and L. Welder are with Climate Analytics GmbH, Ritter Str.3, 10969 Berlin (e-mail: himalaya.birshrestha@climateanalytics.org, ursula.fuentes@climateanalytics.org, andreas.geiges@climateanalytics.org, bill.hare@climateanalytics.org, lara.welder@climateanalytics.org).

M. Schaeffer is with the Global Center on Adaptation, Wilhelminakade 149C, 3072 AP Rotterdam, The Netherlands and Climate Analytics GmbH, Ritter Str.3, 10969 Berlin (e-mail: michiel.schaeffer@climateanalytics.org).

M. Gidden was with the International Institute for Applied Systems Analysis, Laxenburg, Austria. He is now with Climate Analytics GmbH, Ritter Str.3, 10969 Berlin (e-mail: matthew.gidden@climateanalytics.org).

II. Model Framework and Analysis Methodology

The AUSeMOSYS model is developed and enhanced based on the Open Source Energy Modeling System (OSeMOSYS). OSeMOSYS is a full-fledged systems optimization model for long-run energy planning [4]. OSeMOSYS (and thus AUSeMOSYS) is a cost-optimization model based on the linear programming optimization method. The objective function represents minimization of overall system costs, which is subject to various equations and constraints, representing the characteristics of the energy system and its various components. For an in-depth review of the mathematical formulation of the model we refer to [4]-[7]. For additional model enhancements conducted through the development of AUSeMOSYS we refer to [8].

As a bottom-up energy system optimization model, AUSeMOSYS allows for a detail representation of technological characteristics of the energy system. AUSeMOSYS is a multi-sectoral model, which provides a flexible framework to represent different interacting energy sectors and to perform a systematic analysis of the implications of various levels of sector-coupling. In addition, as a multi-regional model, it further allows to analyze the effects of cross-regional integration. This enables us to investigate the synergies of sector-coupling and transmission extension in a cost-optimal, renewable-based Australian energy system.

The model consists of 7 regions: New South Wales (NSW), Queensland (QLD), South Australia (SA), Tasmania (TAS), Victoria (VIC), Western Australia (WA), and Northern Territory (NT). The detail regional structure of the model allows to represent spatial discrepancies in renewable supply and demand. It further enables us to quantify the power transmission capacities for the physical integration of VRES. The optimization is performed intertemporally over a time horizon until 2050, by assuming perfect foresight. The new capacities of various technologies, energy output by fuel and technology, transmission grid capacities, energy-related CO_2 emissions as well as overall system costs are determined by the optimization for each model region. The model flowchart, including data inputs, model constraints and methodology as well as model output is depicted in Fig. 1.

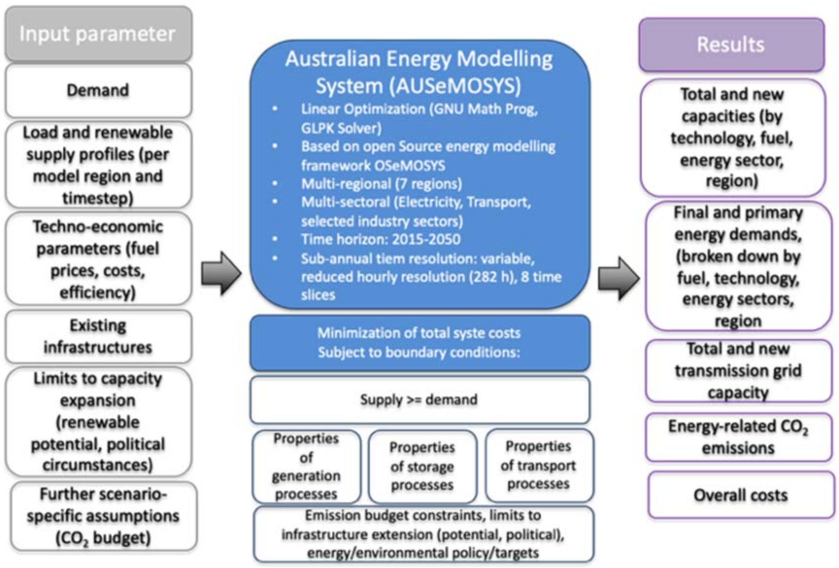


Fig. 1 Flowchart of energy system model applied in this study [9]

The transport sector in the model covers two broad transport service demand categories, passenger and freight road and rail transport. These are quantified in terms of vehicle-kilometre (vkm) and tonne-kilometre (tkm). Fig. 2 visualizes the reference energy system (RES) that shows the link between the electricity and transport sectors as modeled in the current version of AUSeMOSYS. A broad range of power generation technologies on the electricity supply side as well as various existing and future vehicle types (e.g. cars, buses, trucks) and fuel supply options are depicted. For the car fleet, two types of electric vehicles, pure BEVs and plug-in hybrid electric vehicles (PHEVs) are taken into account. For the PHEVs, separate electric- and gasoline/diesel-mode efficiencies are implemented. Additionally, indirect electrification of the fleet is considered through application of renewable hydrogen in FCEVs.

III. Input Data and Scenario Assumptions

According to Fig. 1, various input parameters are applied in the optimization model to represent the Australian energy system's characteristics and exogenous boundary conditions.

First, the electricity demand projections are based on the "Central Scenario" projections by [10], applying central assumptions about population and economic growth. This includes the operational demand excluding the electric vehicle (EV) consumption because the uptake of EVs and the additional electricity demand is treated endogenously by the optimization model. Base projections for the passenger and freight transport activity are based on the continuation of recent trends, assuming a growth rate of 1.1% per year over 2019-2050 for both passenger and freight transport.

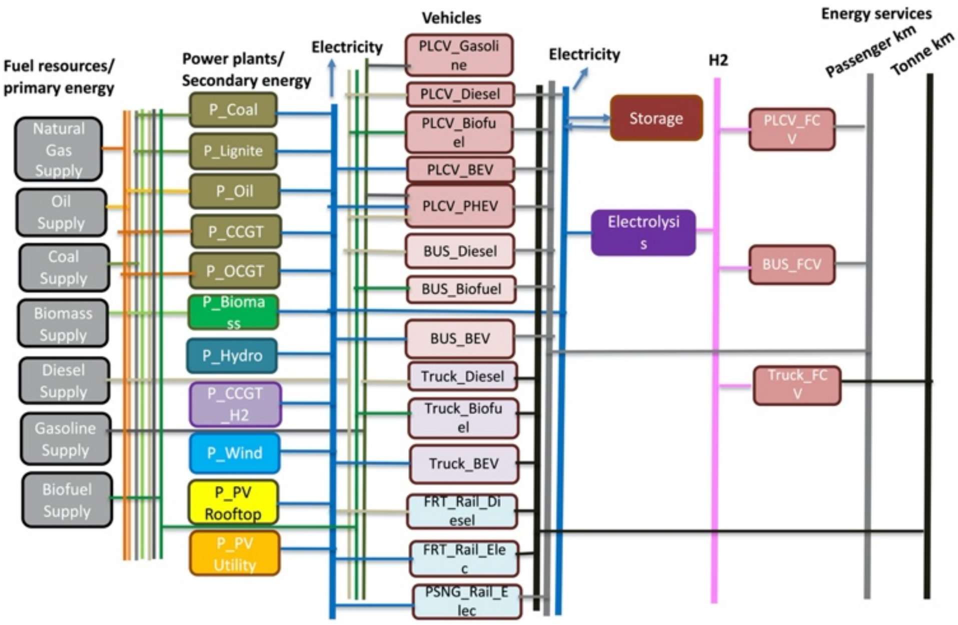


Fig. 2 RES of the transport and power sector modules [9]

Hourly capacity factors of solar PV and wind were calculated based on the data from renewables.ninja for the meteorological year 2018 [11], [12]. The maximum capacity of solar PV and wind capacities that can be installed at each model region is restricted to the available potential as evaluated and informed by various studies [2], [13]-[17]. The capacity of existing power plants at each model region has been obtained from the UDI World Electric Power Plants Data Base [18]. Inter-regional power transmission is modeled as trade-based interconnections, while assuming one representative node per model-region. The existing transmission capacity between model regions has been obtained from [19]. A generic transmission technology is assumed with specific investment costs of 306 US$ per km and MW, in line with the ranges given in the literature [20], [21]. A transmission loss factor of 4% per 1000 km is assumed based on [22], [23]. The techno-economic parameters of various power plant technologies and storage systems have been informed by an extensive review of the most recent studies and data sources [6], [7], [10], [24]-[37].

Energy efficiency of different vehicle types and improvement rates over future periods have been assumed according to the most recent studies and Australian-specific data sources [2], [31], [38]-[46]. Internal combustion, battery electric and fuel cell vehicle cost assumptions are based on the proposed ranges given by [29], [31], [47], [48].

The power production by technology and fuel type at each model region over the historic period (2015-2019) has been calibrated according to the Australian energy statistics [49], [50]. The transport sector module includes five modes of transport: personal cars and light commercial vehicles, buses and passenger trains as well as trucks and freight trains. The transport module is calibrated for each mode of transport based on final energy use by fuel type, annual vehicle-kilometres, and fuel/energy efficiency according to the Australian energy statistics from [39], [51]. Finally, CO_2 emissions over the historic period from the Australian Department of the Environment and Energy (DEE) [52] is applied to validate the model results in terms of CO_2 emissions from the electricity supply and the transport sector. The CO_2 emissions from the power sector reached to 180 million tons in 2019; applying the calibrated model, total CO_2 emissions of the year 2019 were estimated at 179 million tons, which shows only 0.3% deviation. Model results in terms of total CO_2 emissions from the Australia's road and rail transport are also in good consistency with historic emissions, which are estimated at 89 million tons in year 2019 in accordance with historic emissions.

IV. Scenario Analysis

A. Scenario Framework

In addition to the main model input parameters elaborated in Section III, several scenario-specific assumptions and boundary conditions affect the cost-optimal configuration of the energy system. Such exogenously imposed boundary conditions include, for instance, the level of cross-sectoral integration and cross-regional interconnection as well as implied climate policies among others. Thus, we study the implications of these key influencing factors through our scenario analysis in this section.

Here, we model a "Sector-Coupling" scenario (SC), where the electricity and transport sectors are linked through direct use of electricity in BEVs as well as indirect electrification by applying hydrogen as fuel in FCEVs. In addition, this scenario is characterized by a strong growth of renewables, in particular solar and wind power generation, mainly driven by the given tight CO_2 emission constraint. In this scenario, we apply a total CO_2 budget of 3.6 $GtCO_2$ over 2018-2050. This scenario also assumes an annual growth of inter-regional power transmission capacities at 10% per year. The results of the "SC" scenario are compared against a "Reference" Scenario. The latter has no assigned CO_2 budget and is characterized by a very limited level of SC as well as dominance of fossil fuels and emission-intensive technologies across all modelled energy sectors. Table I presents the scenario framework applied in this study.

TABLE I
SCENARIOS AND UNDERLYING ASSUMPTIONS

	Reference Scenario (REF)	SC
Emission constraint	No emission constraint	CO_2 budget constraint at 3.1 $GtCO_2$ over 2018-2050
Energy system: Energy technology change	Slow: dominance of fossil-fuel based technologies	Rapid: Renewable transition dominates the transformation
Energy system: Sectoral integration	Very limited	Strong electrification of end-use sectors (BEV, FCEV, PtG)
Inter-regional power transmission	Limited reinforcement of NEM-wide trans grid capacities at 5% per year	Maximum annual growth rate of inter-regional capacities at 10% per year
Transport activity and modal shift	Base: 1.1% per year over 2019-2050 for both passenger and freight transport	pkm/tkm transport activity remains at the same level of today

B. Optimization Results

The development of power production by fuel type over time is visualized in Figs. 3 and 4 for the REF and SC scenarios, respectively. Mainly driven by the implied tight CO_2 budget, strong growth of renewable generation alongside strong electrification of the transport sector is noticed in the "SC" scenario.

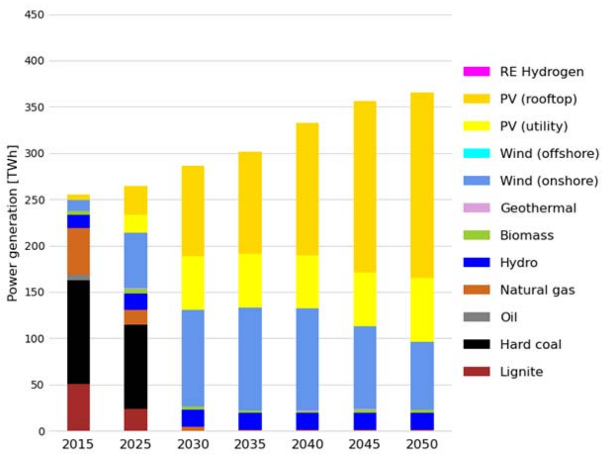


Fig. 3 Power production mix over time for SC scenario (aggregated results for total Australia)

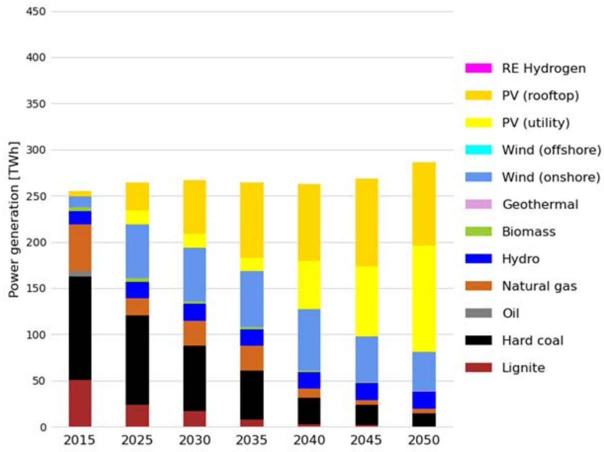


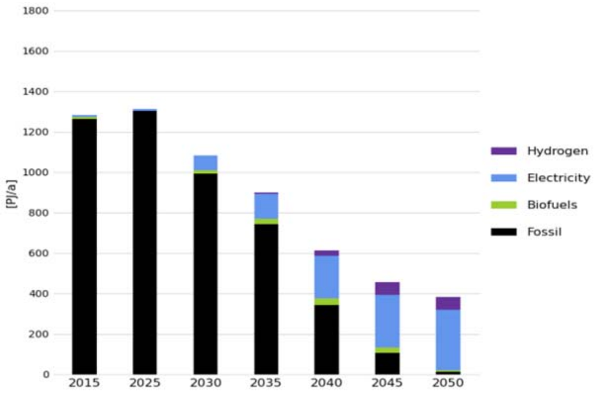
Fig. 4 Power production mix over time for REF scenario

The power production mix in the REF scenario is characterized by the dominance of fossil fuels with coal-fired plants operating until the end of the modeled time-horizon. In. the CO_2-constrained scenario, SC plays a major role as an additional system flexibility dimension alongside the inter-regional power transmission to facilitate integrating high shares of VRES. Correspondingly, in the "SC" scenario, the electricity demand increases by 35% relative to 2015 levels. Fossil fuel generation substantially declines from 2020 onwards, and full renewable supply is achieved by 2035. The renewable power generation is dominated by wind power and solar PV, complemented with lower shares from hydro, biomass, and geothermal energy.

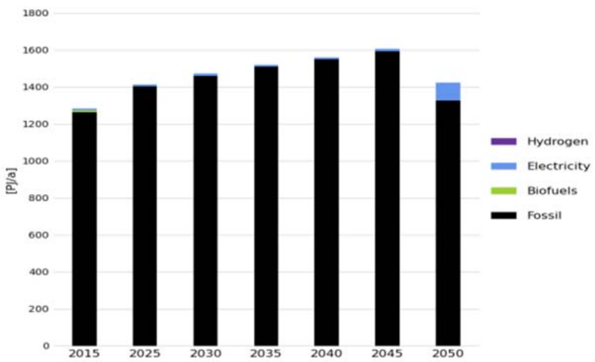
Fig. 5 shows total Australia's land-based transport energy use by fuel type for different scenarios. In the SC scenario, a shift towards more efficient modes of transport, in particular from road transport to railways, plays a key role to reduce fossil energy demand over the transitional period until full electrification of the transport sector is achieved. Fossil fuel-based ICEs completely phase out by 2050 in the "SC" scenario. Full electrification of the car fleet in parallel to decarbonization of the power sector leads to the complete decarbonization of Australia's transport sector by mid-century. For comparison, in the REF scenario, fossil-based ICEs account for a major share of the transport activity over the complete modeled period.

Fig. 6 shows the passenger road vehicle mix over time for the SC scenario. By 2050, passenger road transport will be fully electrified, with a BEV share of about 80% and FCEV share of 20%. Fossil fuel-based ICEs completely phase out from the passenger road car fleet by 2050.

Fig. 7 shows the development of freight activity by mode and vehicle type over time under the SC scenario. To achieve the stringent mitigation targets, ICEs completely phase out from the freight road fleet and are fully replaced by electric and fuel-cell trucks until 2050. Currently, Australia's freight railways is dominated by diesel locomotives; however, under tight CO_2 budgets, the electrification rate of freight trains increases substantially over time in parallel to the decarbonization of the Australia's power sector.



(a)



(b)

Fig. 5 Australia's transport energy use by fuel type for different scenarios: (a) SC scenario; (b) REF scenario

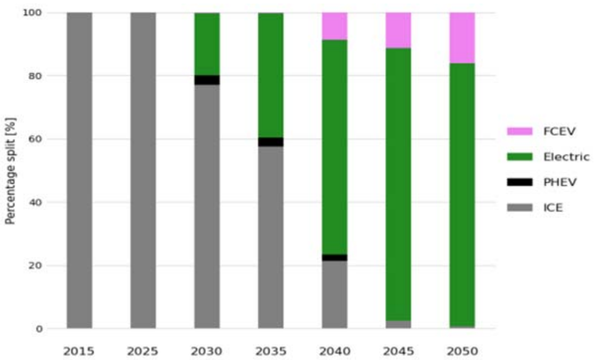


Fig. 6 Passenger road vehicle mx over time for the SC scenario

V. Conclusion

In this study, the multi-sectoral energy system optimization model, AUSeMOSYS, has been applied for analysis of the long-term evolution of the Australian energy system under various boundary conditions. In particular, we investigated the implications of linking the electricity and transportation sectors for achieving the stringent mitigation targets. To facilitate integrating high shares of VRES across all the energy sectors in line with the proposed ambitious mitigation targets, there is a need for an enhanced cross-sectoral integration parallel to the decarbonization of the power sector. Direct electrification of passenger and freight transport fleet through BEVs complemented with indirect electrification through extensive use of renewable hydrogen in FCEVs plays a major role for the complete decarbonization of the transport sector. The low-carbon transformation is further facilitated through major shift towards less energy-intensive modes of transport, moving away from personal cars towards efficient modes of public transport, and in particular, rail transport as the most energy-efficient means of mobility.

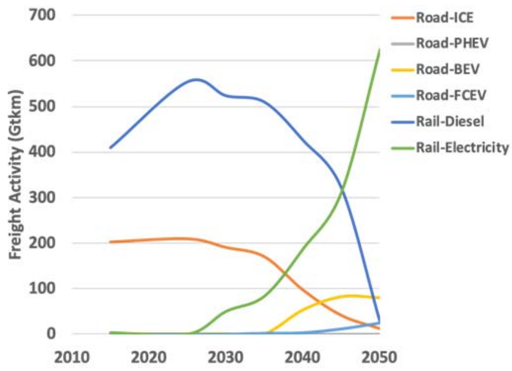


Fig. 7 Freight activity by vehicle type over time for the SC scenario

It is worth mentioning that the energy system cost-optimization models like AUSeMOSYS are solved through inter-temporal optimization over a long-term horizon, by assuming perfect foresight. The model results should thus not be interpreted as predictive or directive. Such bottom-up modeling approach applied in this study rather provides a robust analytical basis to analyse systematic effects and interactions between various energy sectors and components. It additionally provides valuable insights about plausible least-cost decarbonization pathways of the Australia's energy system in line with the proposed ambitious climate targets. Future research could focus on one hand on the inclusion of further energy sectors as well as non-CO_2 greenhouse gases, moving towards the fully integrated Australian energy system.

Acknowledgment

Authors want to express special thanks to Konstantin Loeffler for the interesting discussions and comments with respect to input data and assumptions through the model development process.

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