A preliminary scenario modelling tool to investigate resilience, renewable energy integration, and multi-sectoral decarbonization in Pacific energy supply chains: Fiji case study

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Abstract

Pacific Island Countries and Territories (PICTs) are heavily reliant on fossil fuel imports to fulfill their energy needs, resulting in high and volatile energy costs. As a result, most PICTs have ambitious renewable energy targets as a means of reducing reliance on imported fuels, lowering energy costs, and mitigating the emissions associated with energy production, and there is increasing interest in electrification of transport and other sectors to advance decarbonisation objectives. However, the adoption of renewable energy and broader decarbonisation efforts have been limited, amongst other factors, by a lack of appropriate tools to support energy planning across these economic sectors. This study presents the development of a preliminary open-source scenario modelling tool – the *Energy Transition and Resilience Planning Tool* (ETARP) – to investigate energy resilience as well as the impacts and requirements of transitioning to renewable energy and electrifying various economic sectors to meet strategic energy and emissions targets in PICTs. To demonstrate the capabilities of the tool, Fiji is adopted as a case study for the Pacific. In particular, scenarios for its net-zero and 100% renewable energy targets are parametrised and investigated in terms of resilience, fuel imports, energy supply and consumption, and emissions.

Keywords: Pacific, Renewable Energy, Fuel Imports, Scenario Modelling, Sectors, Tool, Planning, Resilience

1. Introduction

Pacific Island Countries and Territories (PICTs) face a unique set of challenges relating to climate change and energy (Aleksandrova et al., 2021). They are constituted by small islands and low-lying atolls with few local resources and limited land availability. As such, PICTs are placed downstream in the global energy supply chain, being for the most part energy consumers who rely on fossil fuel imports to fulfill their energy needs (Figure 1, left) (Raghoo et al., 2018; Wolf et al., 2016). This greatly exposes PICTs to high and volatile fuel prices, often resulting in comparatively high electricity prices for consumers and overall high national expenditure on fuel (Figure 1, right) (Atteridge and Savvidou, 2019).

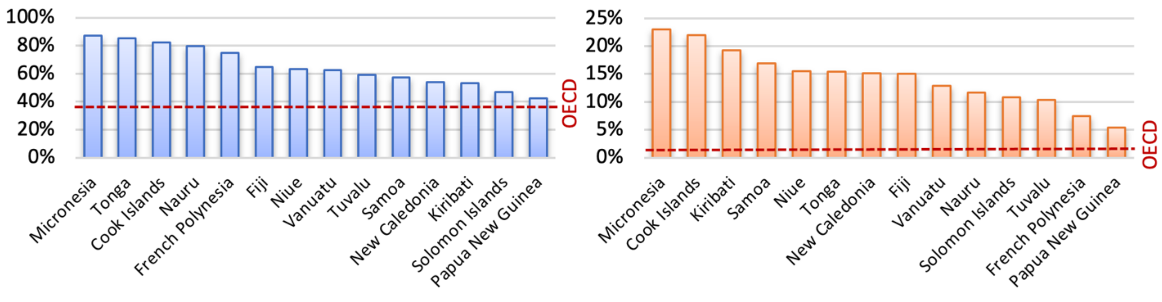

Fig. 1: Fuel consumption as percentage of total energy (Left) and GDP (Right) in 2018. Data: UN (2021), SPC (2019), OEC (2020)

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To overcome the challenges posed by fossil fuel dependence, PICTs have set ambitious targets for increasing the share of renewable energy in their electricity mix (Weir, 2018). Furthermore, many PICTs have also committed to significant emissions reductions as part of international agreements (UN, 2023). To understand pathways to, and implications of, transitioning to clean energy sources and reducing sectoral emissions, analysis of energy consumption across various economic sectors is required (Gargiulo and Gallachoir, 2013). While several sector-coupling modelling tools do exist to investigate the interdependencies between energy production and sectoral consumption (Groissböck, 2019), research has highlighted that there is a lack of tools and data that specifically support energy planning and decision-making in PICTs (Lucas et al., 2017; Michalena et al, 2018; To et al., 2021). Namely, PICTs need specific tools that incorporate energy resilience, enable scenario modelling for specific Pacific economic sectors, have integrated energy data from a variety of sources, and help identify strategies relevant to key Pacific policy objectives (e.g. fossil fuel import reduction).

2. Scenario Modelling Tool Development

To accommodate these specific needs, a preliminary open-source scenario modelling tool has been developed to investigate energy resilience and assess the impacts of increasing renewable energy capacity and electrifying various economic sectors in PICTs – the *Energy Transition and Resilience Planning Tool* (ETARP). The tool has been developed in Excel such that it requires minimal training, provides adaptable outputs, and presents ease in integrating the tool's model structures with other tool or interfaces in use by energy planners, policy makers, and engineers. Table 1 summarises the various sheets available in the tool along with their respective functions. Figure 2 shows a screenshot of the main page user interface. The left section of the main page provides a range of input parameters, as well as various forecasting methods. The central section of the main page displays an adaptable dashboard with the main graphical outputs the tool delivers, subdivided across key categories such as 'Renewable Energy', 'Emissions', and 'Resilience'. The right section of the main page displays raw annual data for key model variables of energy supply chain, such as oil imports, electricity supply, and sectoral consumptions. Users can access more detailed graphs, raw data, and modelling options in the several sheets associated with different sections of the energy supply chain, as shown in Figure 3.

Tab. 1: Tool sheet index and functions

#	Name	Function
1	info	Tool description, sheet index, user manual, and distribution licence
2	MAIN	Main inputs to generate transition scenarios, including goal setting and model parameters
3	Imports, Exports, Bunkering	Annual balancing for fuel imports, exports, and bunkering
4	Supply	Annual balancing for primary energy supply
5	Capacity	Capacity estimation based on selected energy mix
6	Transformations	Annual balancing for transformations
7	Consumption	Annual balancing for sectoral consumption
8	Energy Access	Access to electricity and clean cooking
9	EV	Electric vehicle penetration in land transport fleet using vehicle registrations
10	Hydrogen	Use of hydrogen in energy supply chain
11	Emissions	Sectoral emissions
12	Costs	Cost calculation

13	RE Potentials	Technical potential for each country based on external studies
14	Resilience Indicators	Indicators assessing energy resilience
15	Chevron Profiles	Supply and demand profiles for hourly matching
16	Hourly Matching	Hourly matching for every year of simulation
17	PICTs Data	Database of Pacific Island Countries and Territories

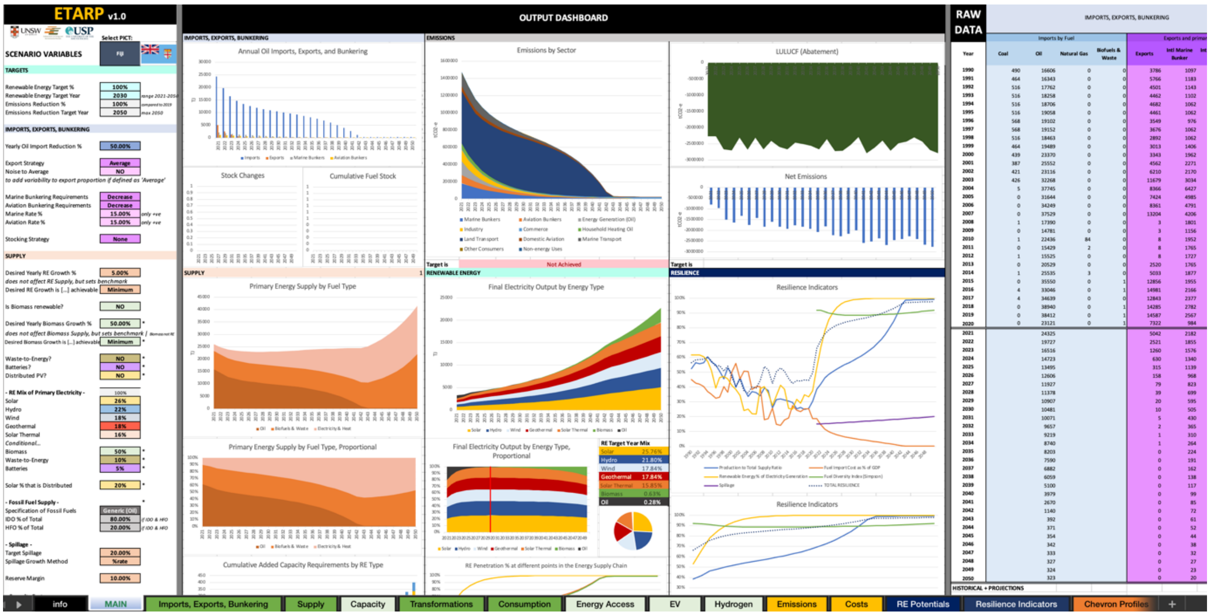

Fig. 2: Screenshot of 'MAIN' sheet

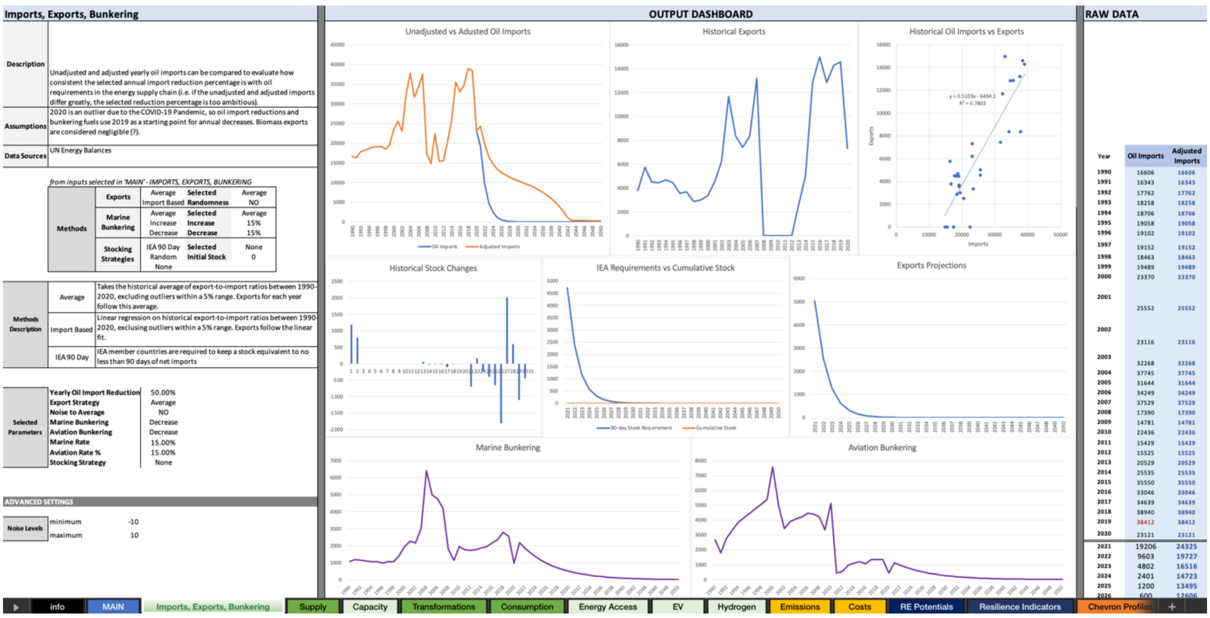

Fig. 3: Screenshot of 'Imports, Exports, Bunkering' sheet

Figure 4 features a flowchart presenting the tool's model structures and variables, input parameters, outputs, data sources, and assumptions. The energy supply chain is subdivided in 4 key categories: imports, exports, and bunkering; primary energy supply; transformations; and consumption – capturing all key energy flows. Input parameters for all types of energy imports, production, and consumption are specified as an annual percentage increase or decrease, in alignment with typical energy policy prescriptions for the region. The model forecasts results for the specified model variables for the period 2021-2050 (with exception of electric vehicle penetration, which starts from 2023 due to recently available data regarding vehicle registrations), and determines whether the inputted targets in terms of renewable energy and emissions have been met. Depending on the user's selection, model variables related to sectoral consumption for each fuel type (i.e. oil, electricity, biomass) are forecasted using one of two methods: linear regression between related variables using historical data (e.g. commerce electricity consumptions vs GDP), or annual percentage changes (increase or decrease). By modelling sectoral consumption in a variety of ways, users can determine how particular economic sectors might change their energy consumption through time to ensure national energy and emissions targets are met.

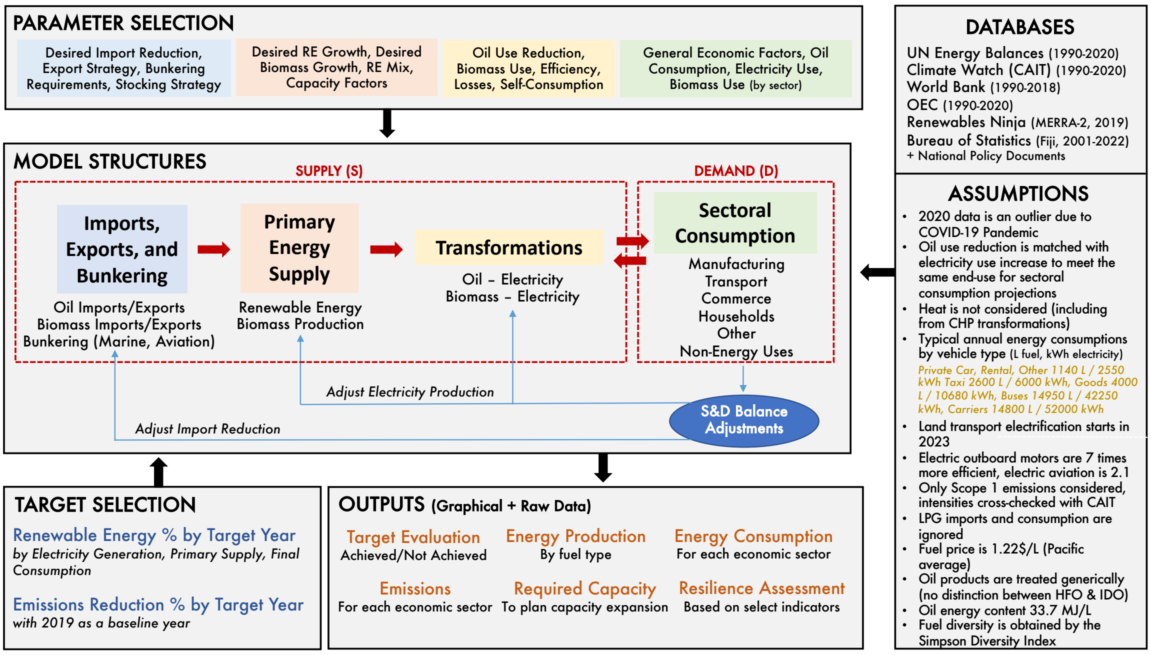

Fig. 4: Scenario modelling tool input parameters, model structures, data sources, assumptions, and outputs

This preliminary version of the tool implements an annual energy supply and demand balancing approach, ensuring that input parameters do not result in an insufficient energy supply to match the forecasted annual demand. Equation 1 is used to determine the required adjustment for each fuel type to balance supply and demand, with $E_{consumption}$ and E_{supply} being determined by the first pass of the model with the initially selected parameters. Equation 2 is used to balance supply and demand based on the required adjustment.

$$\Delta E = E_{consumption} - E_{supply} \qquad \text{(eq. 1)}$$

$$E_{supply} + \Delta E = E_{supply,adjusted} \qquad \text{(eq. 2)}$$

The tool provides several key indicators that can be used to track energy resilience, drawn from key policy documents and literature (Kruyt et al., 2009; Sovacool, 2013; SPC, 2021). These include: production to total energy supply ratio; fuel import costs as a percentage of GDP: fuel diversity index (Equation 3, with n indicating energy units produced by each fuel type and N the total); and renewable energy percentage of total electricity generation.

$$\mathrm{D}_{fuel} = 1 - \sum \frac{n(n-1)}{N(N-1)} \qquad \text{(eq. 3)}$$

3. Methods

This short study adopts Fiji as a case study to test the tool's outputs. Model input parameters were adjusted through various iterations to generate 2 key scenarios related to Fiji's strategic energy and emissions targets: 100% renewable energy by 2030 ('RE100') and economy-wide carbon neutrality by 2050 ('C-0') (Fiji Ministry of Economy, 2018b). Parametrisation of both scenarios is described as follows. Fuel stocking strategies were not considered in either scenario, and bunkering requirements were set to decrease at 2% for RE100 and 15% for C-

0. The specific renewable energy mix for both scenarios is based on the *Low Emission Development Strategy (LEDS) 2018-2050*, with proportions of 26% solar, 17% wind, 22% hydro, 18% biomass, and 17% geothermal in the 'Very High Ambition' scenario (Fiji Ministry of Economy, 2018a). The LEDS was also used to determine annual sectoral electricity consumption increases, averaging around 2%. Capacity factors for solar (18° tilt, 10% system losses) and wind (80m hub height) are adopted from the *Renewables Ninja* database (Pfenninger and Staffell, 2016), while data from NREL was used for other technologies (NREL, 2022). Oil to electricity transformations were set at 34.9% for RE100 and 14% for C-0. Land transport saw 15% and 10% electrification rates for RE100 and C-0 respectively (with goods and carrier vehicles only electrified under C-0), aviation 2% and 10%, and navigation 5% and 10%. Sectoral oil consumption reductions were set at 10% for RE100 and 15% for C-0.

4. Results & Discussion

Results for the two parametrised scenarios are primarily shown in terms of key model variables as well as selected resilience indicators in Figure 5. Key model variables include final oil consumption and import costs to assess fuel dependence, renewable energy growth and emissions reductions (from a baseline) to assess broad energy transition and decarbonisation annual requirements, and renewable electricity percentage to assess target feasibility. Figures 6-13 display more detailed default graphs for a few select output categories, namely fuel imports and energy supply, sectoral consumption, and emissions.

4.1. Overview & Resilience Indicators

Figure 5 shows results for the selected resilience indicators in both scenarios. Annual fuel import reductions average 9.6% for RE100 and 23.73% for C-0, with more significant import reductions under RE100 earlier in the transition. Renewable energy growth averages 4.96% for RE100 and 4.01% for C-0. RE100 is met in terms of electricity generation, but falls 38% short on average to be met in terms of final energy consumption – a target achieved in C-0 through widespread electrification across all sectors. In fact, the final oil consumption ratio for RE100 remains at around 30% in 2050. Emissions reductions under RE100 taper off from 2040 onwards due to limitations in electrifying heavy vehicles, highlighting the need for advanced electrification options to achieve carbon neutrality. Total resilience, obtained by equally weighing all resilience indicators, increases faster under RE100 but reaches higher values in C-0, suggesting that sustained renewable energy growth and sectoral electrification are more effective for overall resilience.

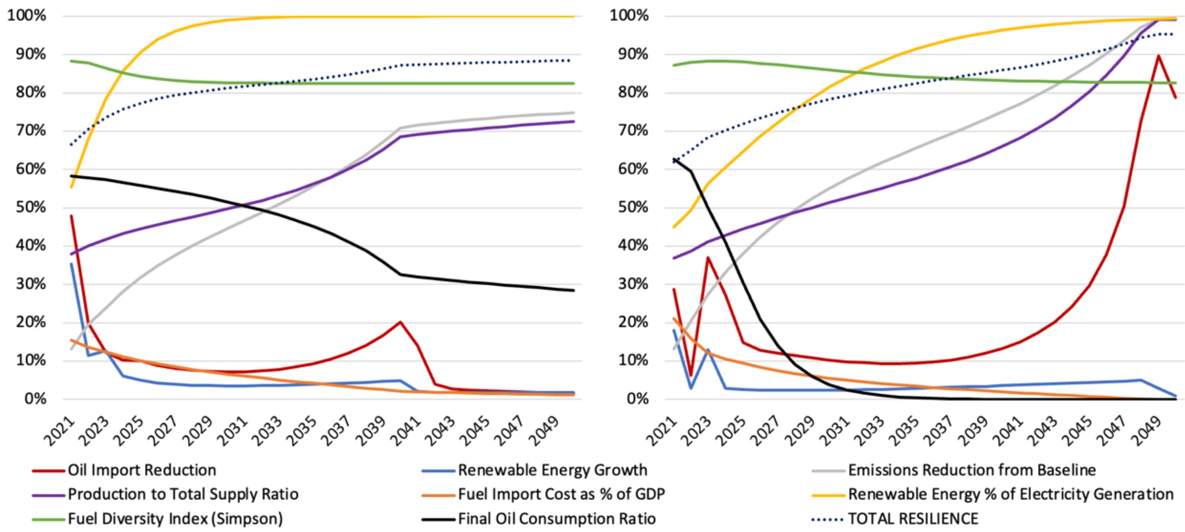

Fig. 5: RE100 (Left) and C-0 (Right), annual percentage changes of key model variables and resilience indicators

4.2. Fuel Imports & Energy Supply

Figure 6 shows the annual oil imports, exports, and bunkering requirements for both scenarios. Differing annual import profiles are due to variations in oil demand across various sectors, with bunkering contributing negligible amounts in the future granted that shipping decarbonisation efforts validate the assumed yearly reduction. Figure

7 shows primary energy supply by broad fuel type – suggesting a greater reduction in overall energy requirements under C-0. Figure 8 shows final electricity outputs by specific fuel type – with biomass growing the slowest due to its primary use in the food and tobacco industry and household cooking.

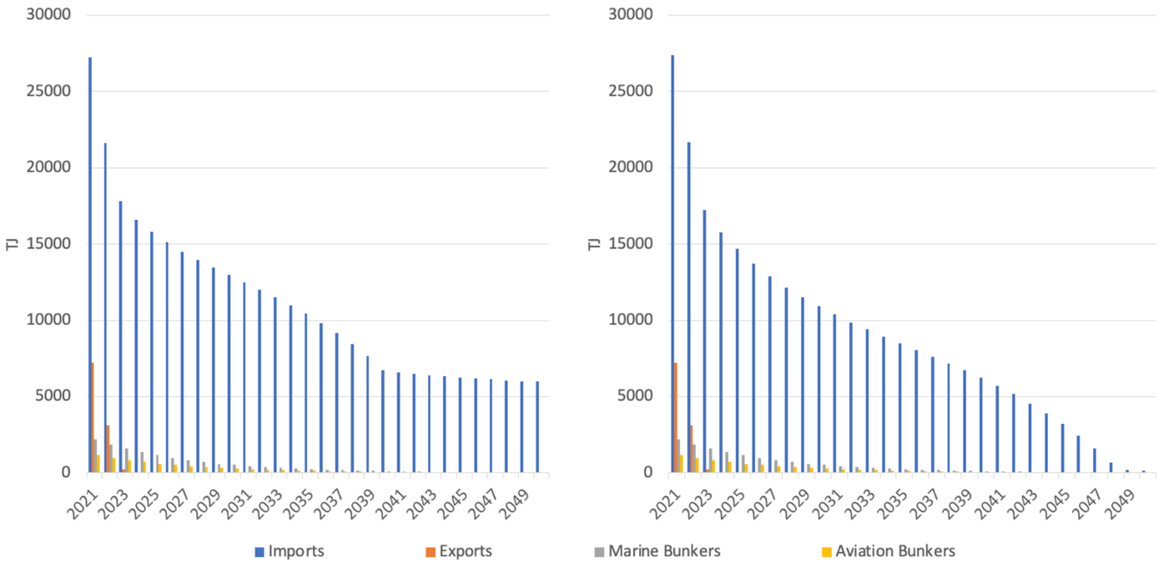

Fig. 6: RE100 (Left) and C-0 (Right), annual oil imports, exports, and bunkering

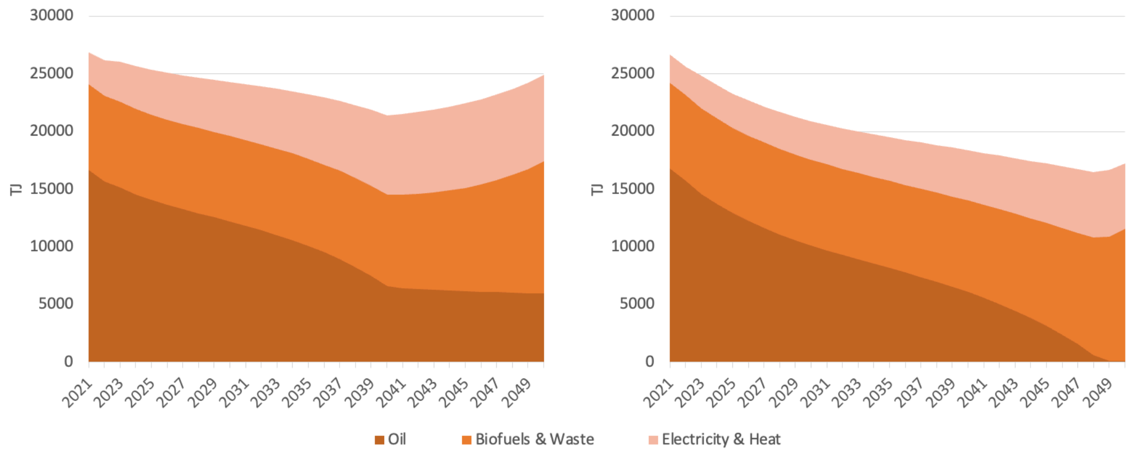

Fig. 7: RE100 (Left) and C-0 (Right), primary energy supply by fuel type

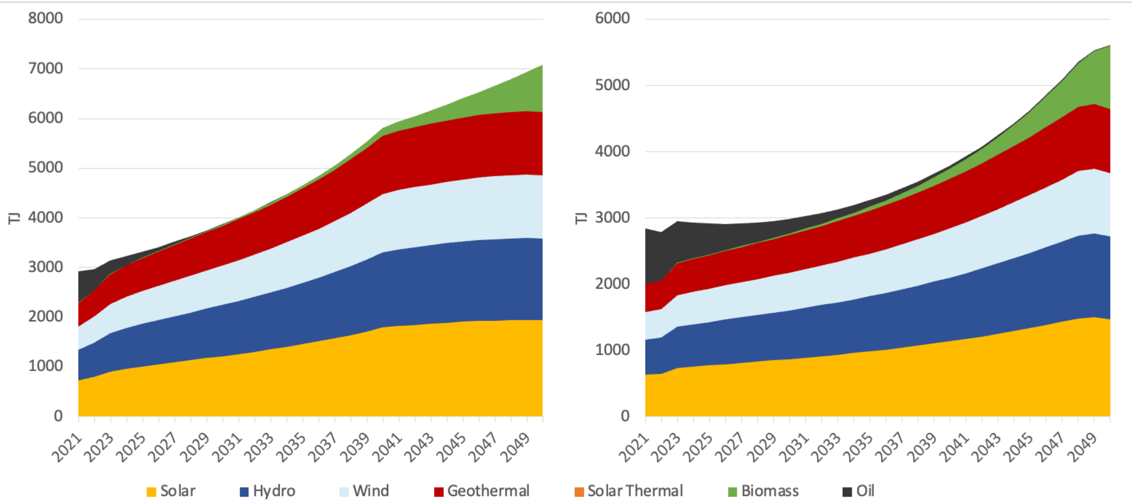

Fig. 8: RE100 (Left) and C-0 (Right), final electricity output by energy type

4.3. Sectoral Consumption

Figure 9 shows final oil consumption for each sector – with land transport dominating both scenarios and requiring a stark and steady decrease in C-0. Figure 10 shows final electricity consumption for each sector. Consistently with the required oil consumption reduction efforts, land transport dominates electricity consumption in 2050 under C-0 – suggesting that electric vehicle integration requires particular attention for long-term decarbonisation. Figure 11 shows final biomass consumption for each sector – confirming that its use is limited to fewer industries. Figure 12 shows electricity consumption for land transport, with goods vehicles requiring the largest amount of electricity due to their prominence and overall vehicle weight.

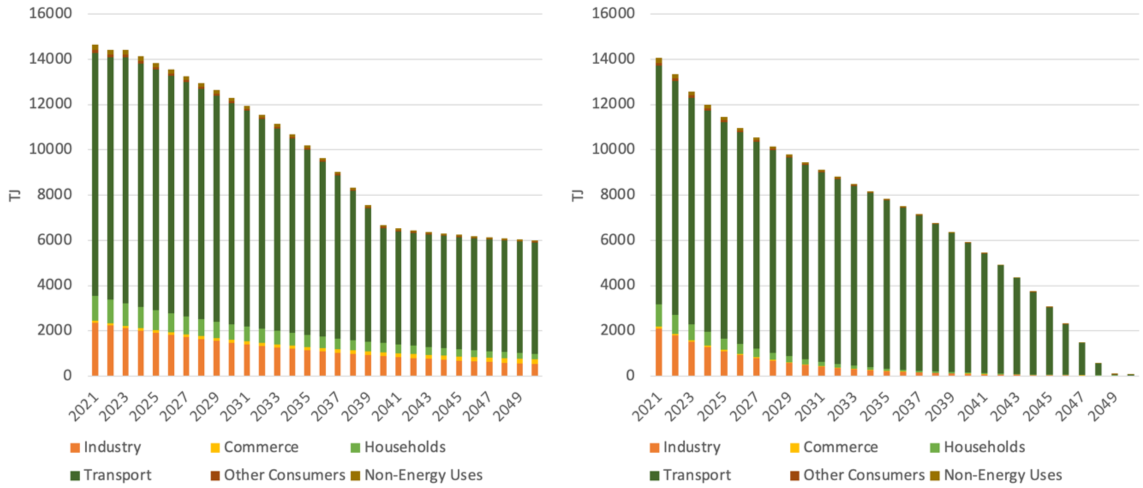

Fig. 9: RE100 (Left) and C-0 (Right), final oil consumption by sector

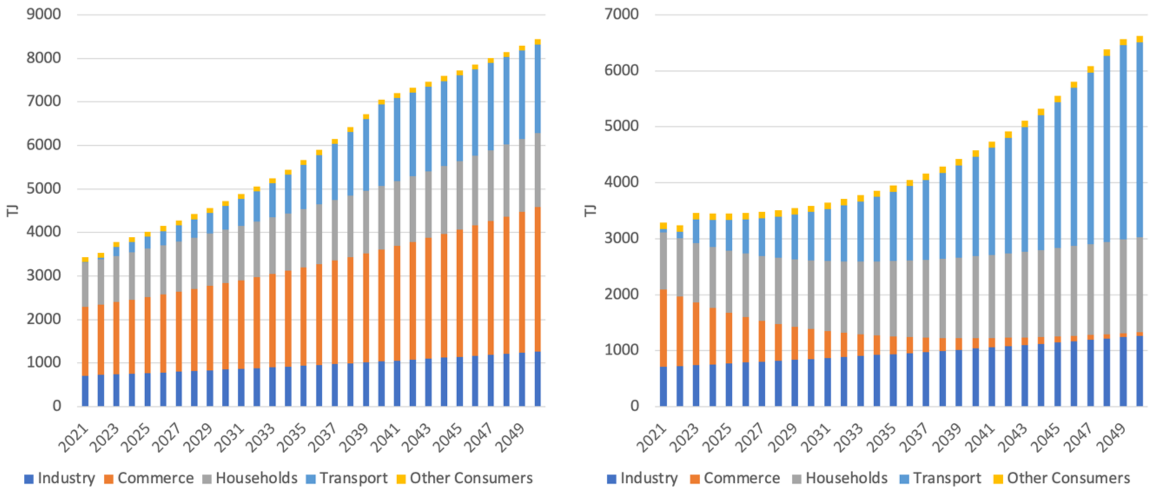

Fig. 10: RE100 (Left) and C-0 (Right), final electricity consumption by sector

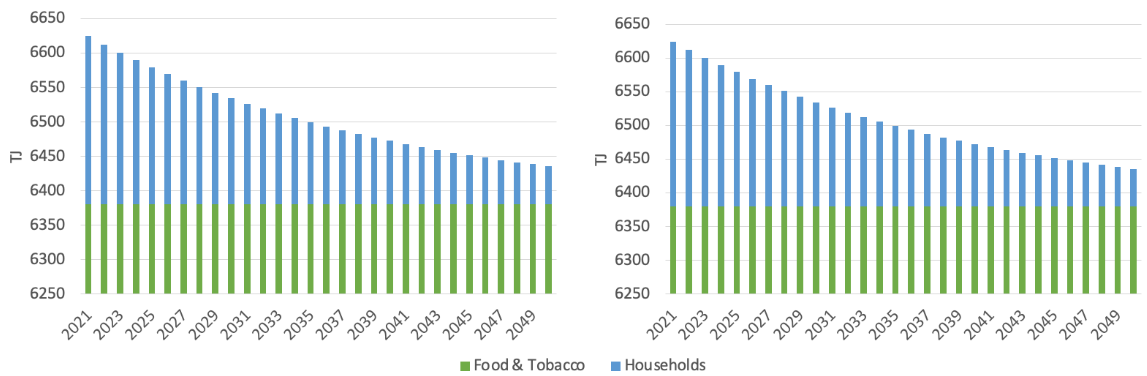

Fig. 11: RE100 (Left) and C-0 (Right), final biomass consumption by sector

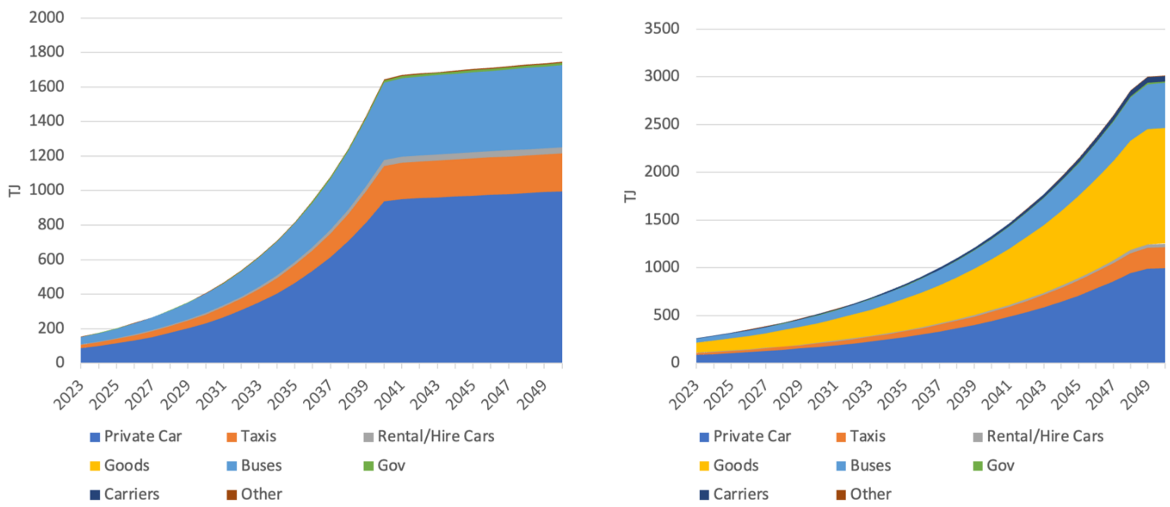

Fig. 12: RE100 (Left) and C-0 (Right), electricity consumption by vehicle type in land transport

4.4. Emissions

Figure 13 shows sectoral emissions for both scenarios – suggesting that decarbonisation efforts should primarily focus on land transport to achieve net-zero targets. In RE100, industry, household heating oil, marine transport, and domestic aviation still contribute to a noticeable portion of emissions in 2050.

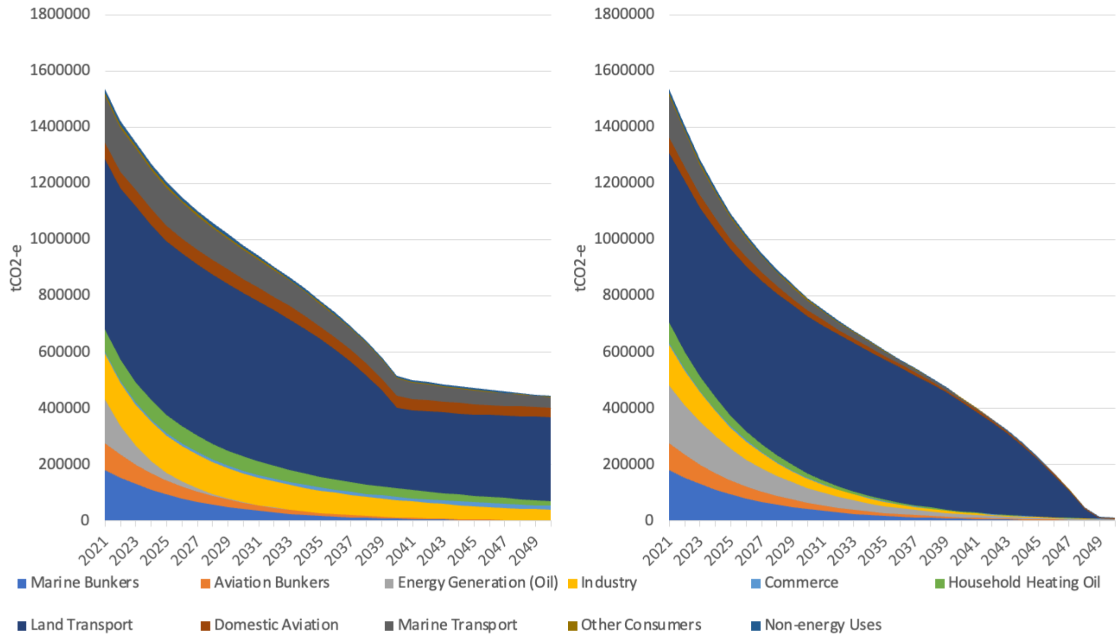

Fig. 13: Fig. 13: RE100 (Left) and C-0 (Right), sectoral emissions

4.5. Interpreting other key outputs for PICTs

As seen in Table 1, this tool also provides outputs regarding other key agendas for PICTs, such as energy access. In both explored scenarios household electricity consumption remains steady, although in countries with lower electricity access levels than Fiji, which sits at roughly 96% (ITA, 2022), selected options for energy access affect overall household consumption. These options include urban and rural population increase/decrease (with the key assumption that urban population is connected to the grid), as well as electrification rates for household cooking (typically done with mostly biomass). Furthermore, the tool also enables the user to select emission abatement rates via land use, land use change, and forestry (LULUCF) – to reflect afforestation and blue carbon management initiatives coupled with national decarbonisation plans – as well as the option to consider biomass "non-renewable" in circumstances where limited land availability may compromise its overall viability as an energy source.

5. Conclusions & Future Work

This study shows that modelling the interdependencies between energy and various economic sectors can provide insights for planning energy transitions to achieve specific targets and enhance resilience. To further develop the accuracy and applicability of the tool, additional parameters should be included or refined to better reflect sectoral transition models (e.g. electric vehicle adoption represented by electric vehicle sales and conventional vehicle decommissioning rather than replacement). Moreover, this study demonstrates the importance of developing extensive national and sectoral energy databases, as well as selecting appropriate input parameters in the development of electrification and decarbonisation plans. Scenario parametrisation should fully capture technical and market developments for various technologies that can reduce emissions (e.g. e-mobility, clean shipping).

Country-specific hourly electricity demand for every sector should also be integrated to enable hourly supply and demand matching, which can better determine capacity requirements and the implications of different renewable energy mixes. Figure 14 shows a preliminary version of this hourly matching for a random scenario – indicating experienced levels of curtailment (with equal curtailment across all energy sources), unmet demand, and overall utility battery requirements (including expected charge/discharge periods). Other planned improvements include capacity factor calculations, cost estimations for renewable technologies, efficiency options for different technology types associated with electrification across sectors, integration of renewable spillage for better capacity estimates, creation of further supply classes that better reflect the Pacific energy supply chain (e.g. on-grid solar and off-grid solar for better capturing energy access), and flexibility modelling (e.g. batteries, demand-side management).

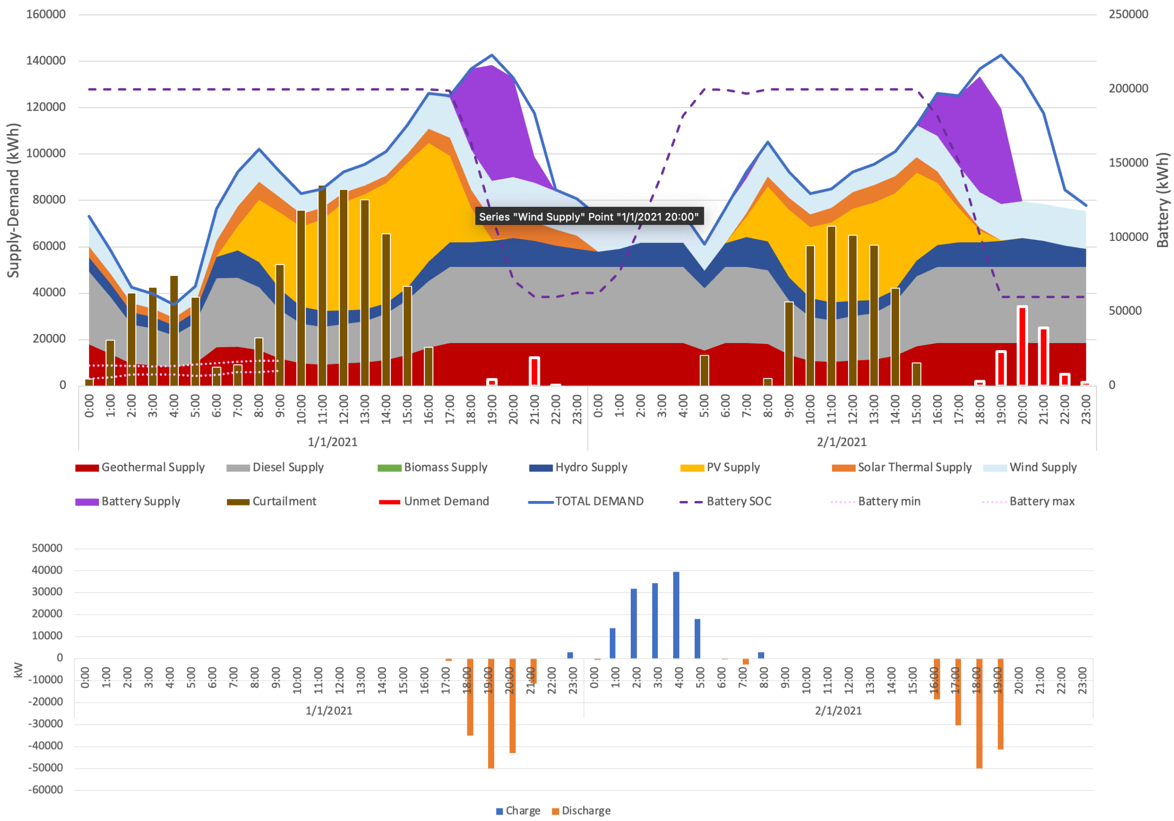

Fig. 14: Hourly supply and demand matching (Top) and overall utility storage behaviour (Bottom) for 2 days (random scenario)

6. Acknowledgements

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