Data to Deal: Developing an Energy Modelling Analytical Workflow to Enhance Political and Financial Decisions

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ABSTRACT

As global environmental challenges increase, there is a need for innovative whole-systems energy modelling approaches to facilitate data-driven decision-making in the field of energy policy and finance. To address this demand, the article presents a comprehensive 'Data to Deal' analytical workflow that integrates seven open-source tools - *Model for Analysis of Energy Demand (MAED), Open Source Energy Modelling System (OSeMOSYS), FlexTool, Climate, Land (Food), Energy and Water systems approach (CLEWs), Ministry Finance (MinFin), and Model for Financial Analysis of Power Sector Projects (FinPlan)* - together to form an exhaustive modelling framework. The modelling framework will include projecting energy demands across various sectors and calibrating the least-cost option to meet the demands whilst taking into account power flexibility, land availability, and water use. Furthermore, the workflow consists of expanding a technical energy systems analysis to include potential financial strategies and projected financial returns. Overall, this article provides both an overview of the analytical workflow and practical guidance for a 'Data to Deal' implementation, and can be utilised by policymakers, analysts, and researchers within the energy modelling, policy, and finance sectors.

1. Introduction

Using open-source energy modelling tools for evidence-based policymaking has proven to be reliable and transparent, accelerating the process of releasing concessionary finance for sustainable development within a nation [1]. However, available studies have so far focused on analysis and results from an individual energy modelling software, rather than a group of software. Thus, these analyses may lack a wider understanding of how policy implementation can affect whole energy systems including varying end-use demand, water for power plant cooling, shareholder's return from energy projects, and so on. Paired with a rise in global environmental challenges, there is a need for innovative whole-systems energy modelling approaches to facilitate data-driven decision-making in the field of energy policy and finance. This article, therefore, aims to bridge the energy modelling gap by detailing a 'data to deal' analytical workflow on soft-linking seven open-source energy modelling tools together. These modelling tools are listed and described below.

1. **Model for Analysis of Energy Demand (MAED)**, a tool developed by the International Atomic Energy Agency [2] to evaluate future energy demand based on a set of consistent assumptions on medium to long-term socioeconomic, technological and demographic developments in a country or a region. Kanté et al. [3] is an example of how the software can be used for electricity demand forecasting of Northern Mali.
2. **Open Source Energy Modelling System (OSeMOSYS)**, a tool developed by KTH Royal Institute of Technology [4], is an open-source linear optimization modelling system for long-run integrated assessment and energy planning of a country or a region. Tan et al. [5] provide an example of OSeMOSYS being utilised for Viet Nam.
3. **FlexTool**, a tool developed by the International Renewable Energy Agency [6] to perform power system flexibility assessments based on national capacity investment plans and forecasts. Taibi et al. [7] showcases how FlexTool was used to analyse Colombia's power system flexibility.

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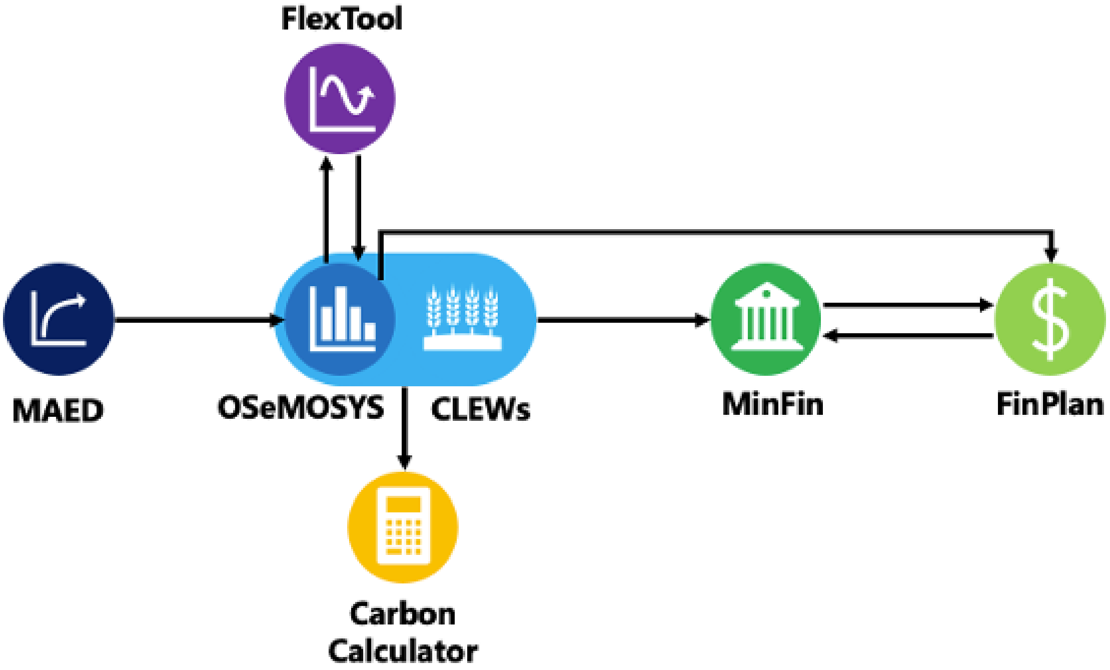

Figure 1: A simple infographic displaying how the seven open-source tools: MAED, OSeMOSYS, FlexTool, MacKay Carbon Calculator, CLEWs, MinFin, and FinPlan, can be utilised together to provide an integrated modelling framework and wider understanding of whole energy systems modelling.

4. **Climate, Land (Food), Energy and Water systems approach (CLEWs)**, an approach developed by the KTH Royal Institute of Technology [8] to analyse the inter-linkages and trade-offs in policy decisions on issues such as investing in clean energy, competing water uses, and agricultural modernization and emission reductions. Howells et al. [8] is an example of how the approach can be used to assess Mauritius' water levels with ethanol generation.
5. **MacKay Carbon Calculator (Carbon Calculator)**, a visualisation platform developed by the United Kingdom Government Department for Business, Energy and Industrial Strategy [9], which aims to create pathways based on 'levels of ambition' to show how such choices can affect carbon dioxide equivalent emissions. The Carbon Calculator has been adopted and adjusted for countries such as Kenya [10] and Viet Nam [11].
6. **Ministry Finance (MinFin)**, a tool developed by Imperial College London and the University of Oxford to support Ministries of Finance in developing a financing strategy for the implementation of certain energy policies and plans within a country.
7. **Model for Financial Analysis of Power Sector Projects (FinPlan)**, a tool developed by the International Atomic Energy Agency [2] that allows an analysis of the financial performance of power plant projects over their lifetime. Shafiqul and Bhuiyan [12] showcases FinPlan being used to assess the financiability of a nuclear power plant in Bangladesh.

The analytical workflow will start with MAED, where demands of the industrial, transport, housing, and services sectors are projected based on a set of assumptions including socioeconomic, technological and demographic developments. These outputs can then be used as pre-defined demands for OSeMOSYS (Section 2.1), with the tool calibrating the least-cost pathway to meet the demands. FlexTool can then be integrated to analyze the power system flexibility, refining the OSeMOSYS model results(Section 2.2), and the CLEWs approach can be incorporated to understand the impacts of energy use and consumption on land availability and water use (Section 2.3). The technical outputs from OSeMOSYS or CLEWs can also be visualized via interactive ambition levers on the Carbon Calculator (Section 2.4). The workflow will then expand from a technical energy systems analysis to include financial planning.

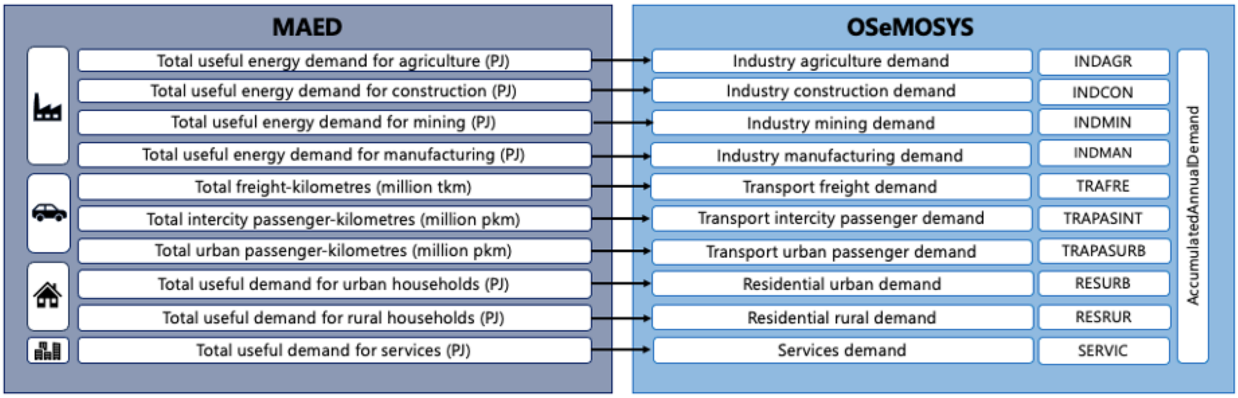

Figure 2: A list of projected industrial, transport, household, and services demand outputs calculated by MAED that can be used as input demand data for OSeMOSYS. The column on the right provides a suggested code name for the respective demands and the OSeMOSYS parameter for which data should be inputted for.

To do this, MinFin is introduced to create a financial strategy surrounding aspects on discount rates, loan repayment period, and more to cover investment costs suggested by OSeMOSYS (Section 2.5). Additionally, FinPlan can be utilised with OSeMOSYS and MinFin outputs to assess the financial returns of a power plant or set of power plants (Section 2.6). Figure 1 shows an infographic of how the seven tools can be utilised together as part of an integrated modelling framework. Overall, the article provides both clarity on the conceptual flow between the modelling tools and practical guidance to execute the analytical workflow for a 'Data to Deal' implementation, and can be utilised by policymakers, analysts, and researchers within the energy modelling, policy, and finance sectors.

2. Analytical Workflow

2.1. MAED to OSeMOSYS

MAED is a tool used to evaluate future energy demand of the industrial, transport, household, and services sectors based on a set of consistent socio-economic assumptions such as population and gross domestic product growth. Alternatively, OSeMOSYS is a tool that calculates the least-cost energy mix to supply a pre-defined demand within a country, region, or sector. This is therefore the first link within the energy modelling pipeline - from MAED outputs, users can obtain the *useful energy demand* of each sector through to OSeMOSYS to calculate the cheapest way to meet these demands.

Figure 2 lists the necessary outputs from MAED and their respective demand names as inputs in OSeMOSYS for the linkage. If the user wishes to include the MAED projections of the different fuel types that may meet the demands, this can be done following an example shown in Figure 3. Note that these fuel types are only dependent on what the user has defined in the 'General information' tab on MAED. For example, if the user has defined three transport fuel types: gasoline, diesel, and electricity, and four transport modes: motorcycle, car, heavy-duty vehicle, and bus, then the number of technologies that will meet the transport demand is twelve: gasoline motorcycle, diesel motorcycle, electric motorcycle, gasoline car, and so on. A list of suggested code names for various vehicle modes by fuel type can be found in the Transport Starter Data Kit [13]. If this method of projecting the fuel demand is followed, a recommended 'buffer' of 20% above and below the projected MAED fuel values should be applied to allow OSeMOSYS flexibility when calibrating a least-cost model. Based on the above, additional inputs for energy demands, technologies, and fuel types may need to be considered in OSeMOSYS to satisfy the connection. To aid the user in creating the respective demands, technologies, and fuel types, Figures 9, 10, 11, 12 in Appendix A.1 display example reference energy system (RES) diagrams for the industrial, transport, household, and services sector that one can adopt, adapt, and apply.

It should be noted that there are still a list of parameters needed for a complete OSeMOSYS analysis that MAED does not provide. This includes techno-economic data on fuel price projections, efficiency of power plant technologies, emission factors, resource availability, and more. Lastly, to ensure consistency throughout the modelling pipeline, the following units on MAED are suggested: *million pkm* for passenger transport activity, *million tkm* for freight transport activity, and *PJ* for energy.

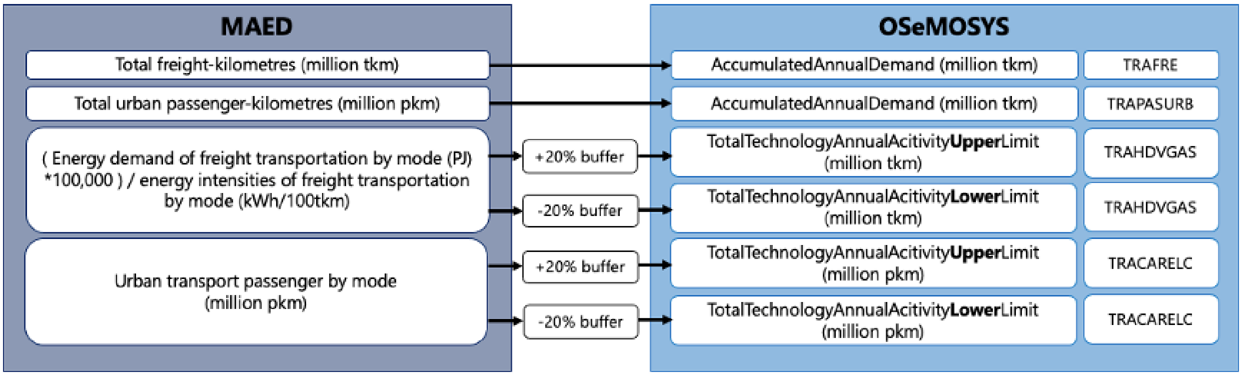

Figure 3: An example of how transport demand by mode and fuel type can be inputted to OSeMOSYS as a constraint. Creating lower and upper limits with a 20% 'buffer' will allow OSeMOSYS flexibility when calibrating a least-cost model. The right-hand side column notes down the suggested technology code name for a gasoline heavy-duty vehicle and an electric car. Further code name suggestions for other vehicle modes and fuel can be found in the Transport Starter Data Kit [13].

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2.2. OSeMOSYS to FlexTool

OSeMOSYS is an integrated assessment and energy planning tool that performs long-term energy system planning and investment optimization, determining the most cost-effective energy system configuration over a long-term modelling period. In the power sector context, OSeMOSYS optimizes the capacities of electricity generation and storage plants and if in the scope of the model, it may also plan if and how end-uses are electrified, affecting the total electricity demand. For example, depending on how much transport is electrified, the total electricity demand to be served by power plants may alter significantly. FlexTool on the other hand, analyzes the short-term and operational aspects of a power system, performing single-year flexibility analyses, to identify potential underlying flexibility bottlenecks and evaluate possible flexibility options, such as the deployment of (additional) electricity storage and the implementation of demand response. Hence, in an integrated OSeMOSYS - FlexTool analysis, OSeMOSYS provides the cost-optimal setup of the power system in the future and FlexTool evaluates the proposed system from an operational perspective. Insights from both tools may better inform decisions about power system infrastructure development, operational strategies, and policy recommendations.

One important aspect the user has to consider when performing an integrated OSeMOSYS-FlexTool analysis is that the modelling approach of the two tools for the power sectors is different. OSeMOSYS models the power sector within the rest of the energy system. Electricity is modelled as a demand commodity consumed in end-use sectors and supplied by power plants. Alternatively, FlexTool deploys a more detailed and topological grid-based approach. The electricity system is modelled as a node (or multiple nodes interconnected with transmission lines), where the power supply technologies and the electricity demand are located. Moreover, FlexTool accounts for power system characteristics (e.g. inertia, reserve provision) and technological options (e.g. electricity interconnections, demand response), which are not included in OSeMOSYS. Ultimately, the two tools differ in terms of temporal resolution. OSeMOSYS is used for long-term multi-year analyses and each year is modelled with some sampled representative timeslices. FlexTool, on the other hand, focuses typically on a single year, which is modelled with a full hourly resolution.

From a technical point of view, OSeMOSYS implementation shall precede the FlexTool analysis. The FlexTool model can be set up -partially- based on the inputs and outputs of the OSeMOSYS model. The key parameters transferred from the OSeMOSYS inputs to FlexTool are the annual electricity demand and the techno-economic characteristics of the power technologies. From OSeMOSYS outputs the key parameter needed for populating FlexTool inputs is the capacity of the power generators and possible electricity storage units. Additionally, in case the OSeMOSYS analysis affects the final electricity demand (as in the example with the electrification of transport described), this parameter shall be sourced from the OSeMOSYS results. The transfer of input and output parameters of OSeMOSYS to FlexTool is illustrated in Figure 4.

It should be noted that a series of parameters necessary for FlexTool, cannot be sourced from OSeMOSYS. FlexTool provides a more detailed representation of power technologies and thus requires additional technology characteristics compared to OSeMOSYS. Typical examples are the so-called flexibility parameters of power-generating units, such

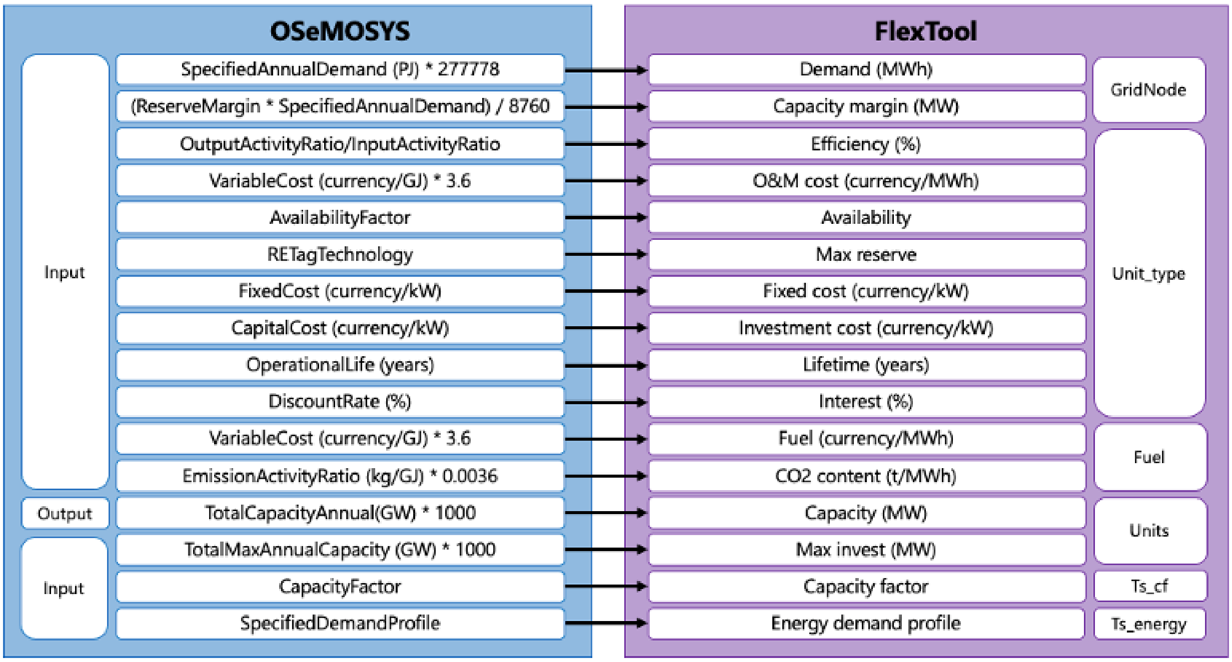

Figure 4: A list of techno-economic inputs and output from OSeMOSYS that can be used as input data for FlexTool. The right column lists the tab name in which the FlexTool input parameters can be found.

as ramping capabilities, and minimum stable load among others. Such parameters need to be sourced from the international literature. Additionally, since the temporal resolution is different, parameters expressed in time series, like the demand profile and the capacity factor profiles of renewable energy plants, cannot be directly transferred from one input file to the other. Nevertheless, it is important to ensure that the full time series used in FlexTool are matching the ones used to produce the representative reduced time series in OSeMOSYS.

In the instance that a FlexTool analysis highlights issues with the power flexibility system, one can delve into two solutions, however, the first option is recommended. If concerns such as curtailment or loss of load are present in the analysis, the user can:

1. Integrate different flexibility options such as electric vehicles, battery storage, power-to-heat, power-to-hydrogen, and demand response. Nonetheless, data regarding these technologies will be required for this sector-coupling analysis.
2. Direct back to OSeMOSYS and revise the capacity results, perhaps updating constraints or technology assumptions so that power flexibility results in FlexTool are addressed.

Detailed hands-on exercises for the soft-link of OSeMOSYS to FlexTool can be found on the CCG Data to Deal Analytical Framework Zenodo repository: `zenodo.org/record/8123555`.

2.3. OSeMOSYS to CLEWs

CLEWs builds upon the robust, open-source and accessible foundation laid by OSeMOSYS to offer an integrated, nexus-based framework encompassing energy, water, land, and climate systems. Thus, unlike the other tools where outputs from one can serve as inputs for another, CLEWs simply builds and expands an OSeMOSYS energy model to include the water, land, and climate.

The optimization algorithms and data structures of OSeMOSYS are either incorporated as-is or adapted to align with the broader, nexus-oriented objectives of CLEWs. This symbiotic relationship allows for a comprehensive exploration of resource systems through the lens of nexus thinking. By adopting a nexus approach, CLEWs transcends sectoral silos to recognize that these systems are deeply interconnected and interdependent [14, 15]. For instance:

- Water for Energy: Energy production often requires significant water use, especially thermal power plants which require water for cooling. More water-intensive energy sources can strain water supplies, impacting availability for other uses.
- Energy for Water: Water production also requires energy inputs, for pumping water from surface and groundwater sources for irrigation, thermal power plant cooling, desalination, and public water supply.
- Land for Energy: Land management for energy production, like growing biofuel crops or building solar and wind farms, can compete with food production and nature. Poor practices like overuse of fertilizers on energy crops can pollute waterways. Deforestation for palm oil-based biofuels impacts climate through lost carbon sequestration.
- Energy for Land: The energy, i.e., diesel, that is used for operating agricultural equipment in the land used for crop cultivation. Other land uses may also require energy in various forms like deforestation
- Land for Water: Agricultural land use strongly influences water quality. Runoff of nutrients, pesticides, and manure from farms degrades water bodies like rivers and lakes. Clearing vegetation for crops can reduce water infiltration into soils and aquifers, affecting supply.
- Land for Climate: Agricultural expansion often contributes to climate change through deforestation and methane emissions from livestock. Sustainable land management like cover crops, reduced tillage, and wetland restoration can help mitigate climate change.

For CLEWs to operate within the OSeMOSYS architecture it needs to abide by the same principles. Namely, it needs to be demand-led. In the same way, OSeMOSYS has to have a final energy demand i.e., the requirement or ‘answer’ that the code has to ‘reach’ to produce results, the same is required for CLEWs. In terms of the land component, this requirement comes in the form of a land use demand. For example, every type of land use represented in the model i.e., tree cover, inland water, built-up land etc. needs to have a form of ‘demand’ present. Typically, CLEWs models also incorporate arable land which is ‘governed’ by a demand for the specific crops represented in the model. Additional complexity can also be added here in the form of low-input arable land (i.e., rainfed crops) and high-input arable land (i.e., irrigated crops). Similarly, demand is also required for water and can be represented in terms of accumulated industrial, residential, commercial and agricultural demands.

Figure 5 is a developed RCLEWs diagram, showcasing the key interlinkages between specific commodities and technologies including how Energy is connected to Land and Water modules. The interlinkages shown in this figure, for example, include water for energy, energy for water, and land for energy. Water for energy is represented through water for cooling (*PWRWAT*), whereby water becomes an input to fossil fuel power plants. Energy for water is represented through energy needed for pumping water (*ELC002*), as an input to gas and coal power plants. Land for energy is represented through the use of crops to create biofuels for transport, whereby maize produced within the model is used to meet a demand set for biofuel. This link crucially highlights the potential for further representing transport in a CLEWs model in a similar way to OSeMOSYS. This figure currently suggests only a simplified representation of possible inter-linkages, with more being possible.

2.4. OSeMOSYS to the MacKay Carbon Calculator

The MacKay Carbon Calculator is an interactive web-based tool designed to enable users to explore different scenarios for national energy consumption and production. By choosing ‘levels of ambition’ for decarbonising different sub-sectors of the energy sector, users can visualise the potential impacts of different energy choices on the national carbon footprint, thereby promoting a deeper understanding of sustainable energy strategies. These levels, determined through expert consultations, chart potential energy trajectories. The tool displays projected energy mixes and carbon emissions up to 2050/2100 based on user choices, utilizing an underlying simulation model of the energy sector developed in Excel. The calculator was first made for the UK and now exists for many countries in the Global South.

To link OSeMOSYS and the Carbon Calculator together, one can produce an interactive visualisation tool for OSeMOSYS akin to the user-friendly interface offered by the Carbon Calculator. In this adaptation, results from the Carbon Calculator simulation model are replaced by OSeMOSYS results instead. The visualized results on the interface will be adjusted to display OSeMOSYS costs, and graphs may be further customised to target different stakeholder groups. An important consideration going forward will be the choice of levers. OSeMOSYS can accommodate fewer levers than the Carbon Calculator as it is limited by the number of scenarios which can be pre-run. For instance, 5

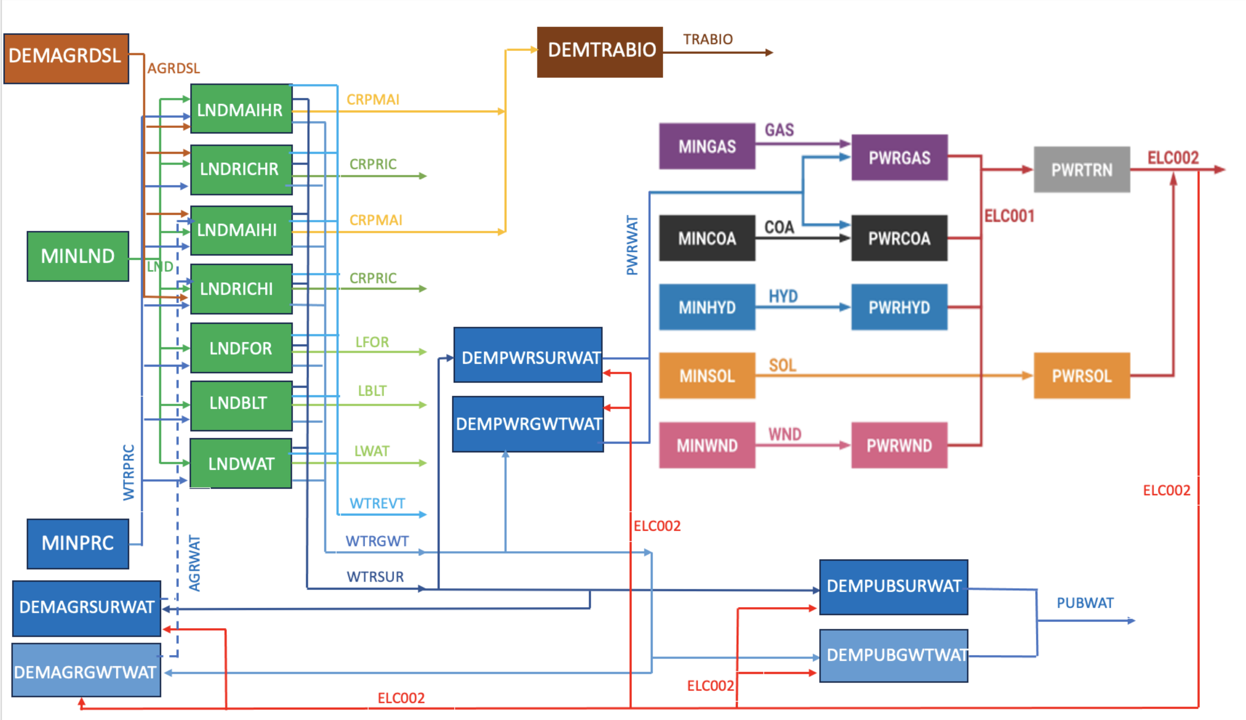

Figure 5: A developed RCLEWs diagram outlining the key commodities and technologies. The figure displays the interlinkages modelled within the CLEWs system. The full list of naming conventions can be found in table A.2 in Appendix A.2.

levers with 4 levels of ambition each corresponds to 1024 possible scenarios, each taking several minutes to run. In contrast, the Carbon Calculator can handle 45 such levers. This is not necessarily a limitation as each OSeMOSYS scenario is an optimised solution, but thought should be given to the type and number of levers and ambition levels included. Thus, the integration process will require: (1) Using a script to run OSeMOSYS scenarios for all desired lever level combinations; (2) Following an adapted version of the existing Carbon Calculator visualisation process to create a webpage for OSeMOSYS visualisation; and (3) Optionally adapting the visualisation script to customise the graphs and levers to be displayed in the visualisation. Note that scripts for (1) and (2) are currently being developed as future work.

2.5. OSeMOSYS and FinPlan to MinFin

MinFin is an analytical tool designed to examine national-level financing strategies to facilitate discussions with Ministries of Finance by translating technical demands into clear financial strategies. Users can determine the fiscal viability of implementing a financing strategy in a country based on recent history and forward-looking projections. The MinFin input process is structured around three fundamental pillars: (1) financing sources: this pillar examines the historical experience of the country in financing energy projects, including the types of financiers that have participated and the terms that have been available; (2) funding baselines: this pillar identifies the resources that are available in the energy sector of the country that can be used to service debt and finance projects. Information for the funding baseline and financing sources can be primarily sourced from government reports and existing literature; (3) financing needs: this pillar sources OSeMOSYS outputs, to discern the annual capital investment required from long-term energy plan scenarios.

Key outputs from OSeMOSYS, as depicted in Figure 6, serve as essential parameters for input into MinFin. These outputs include capital investment, operating costs and emissions, which are noted below.

- Capital investment: OSeMOSYS generates vital capital investment outputs, forming the foundation for estimating future power plant financing needs in MinFin.

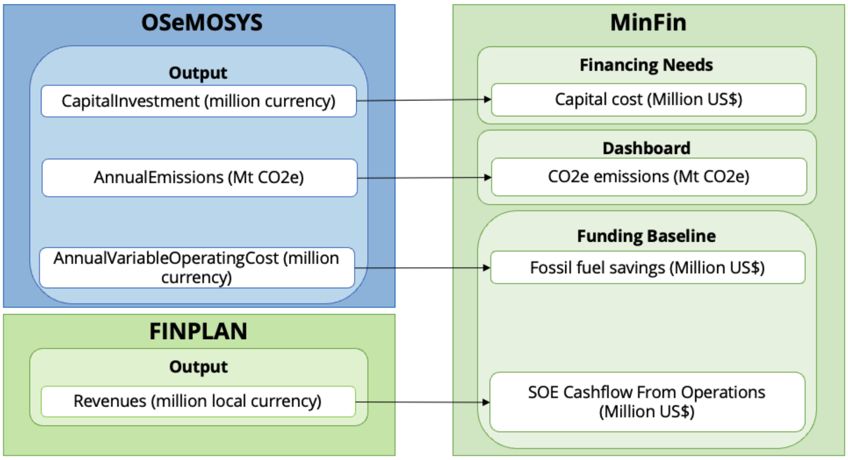

Figure 6: A list of techno-economic outputs from OSeMOSYS and FinPlan that can be used as input data for MinFin. The units for both tools are the same, therefore, no additional calculations are needed.

- Operating costs: Furthermore, OSeMOSYS-derived operating cost analysis allows for a comparative assessment of fossil fuel expenses and potential savings between scenarios, adding to a country's funding baseline in MinFin.
- Emissions: Incorporating OSeMOSYS emissions data into MinFin transparently showcases the environmental benefits of transitioning to a scenario such as Net Zero, offering users a strong incentive to pursue more ambitious decarbonisation strategies.

Using the outputs from OSeMOSYS to create a FinPlan model, as explained in 2.6, yields outputs which can be input into MinFin, including project revenue. This revenue can be integrated into the funding baseline of MinFin. For instance, if a country anticipates high export revenues, this income can be included in the pool available for funding capital investments in domestic power projects. Lastly, it is essential to ensure that units are consistent throughout this analytical workflow which may require conversion calculations outside of the models.

2.6. OSeMOSYS and MinFin to FinPlan

FinPlan is a tool that can assess the financial viability of plans and projects, taking into account different technical and financial sources such as plant size, electricity generation, investment costs, discount rates, and so on. From this, FinPlan calculates projected cash flows, financial ratios, shareholders' returns, and other financial indicators. Thus, OSeMOSYS inputs and outputs and MinFin outputs can be used as inputs into the FinPlan tool. The user may use these inputs to model the whole power system, however, this will increase the difficulty in interpreting the results, as they come as a whole. Thus, it is strongly suggested that one type of power plant, or a group of the same type of power plants constructed in the same year, as recommended by OSeMOSYS, be modelled instead. If one is willing to model the whole power system, it is advised to create multiple individual case studies that can be joined together externally.

The user shall extract six outputs and two outputs from OSeMOSYS and MinFin, respectively, as shown in Figure 7. Note that FinPlan has fixed units, therefore, manual calculations from OSeMOSYS are needed to ensure the values are consistent. Values from MinFin, however, do not need to be converted as they are in the same units. Based on Figure 7, electricity quantity and electricity price for the first year can be found in FinPlan's Sales and purchase data sheet. Unit size, investments, O&M costs, and fuel costs are within the Plant data sheet. Note that interest rate and loan term are in Terms of financing of Project loans, under the Sources of financing sub-tab in the Plant data tab. As mentioned in Section 2.5, the revenue output from FinPlan can also be used as an input in MinFin, representing the additional income that can be included in the pool available for funding capital investments in domestic power projects.

Detailed hands-on exercises for the soft-link of OSeMOSYS and MinFin to FinPlan can be found on the CCG Data to Deal Analytical Framework Zenodo repository: `zenodo.org/record/8123555`.

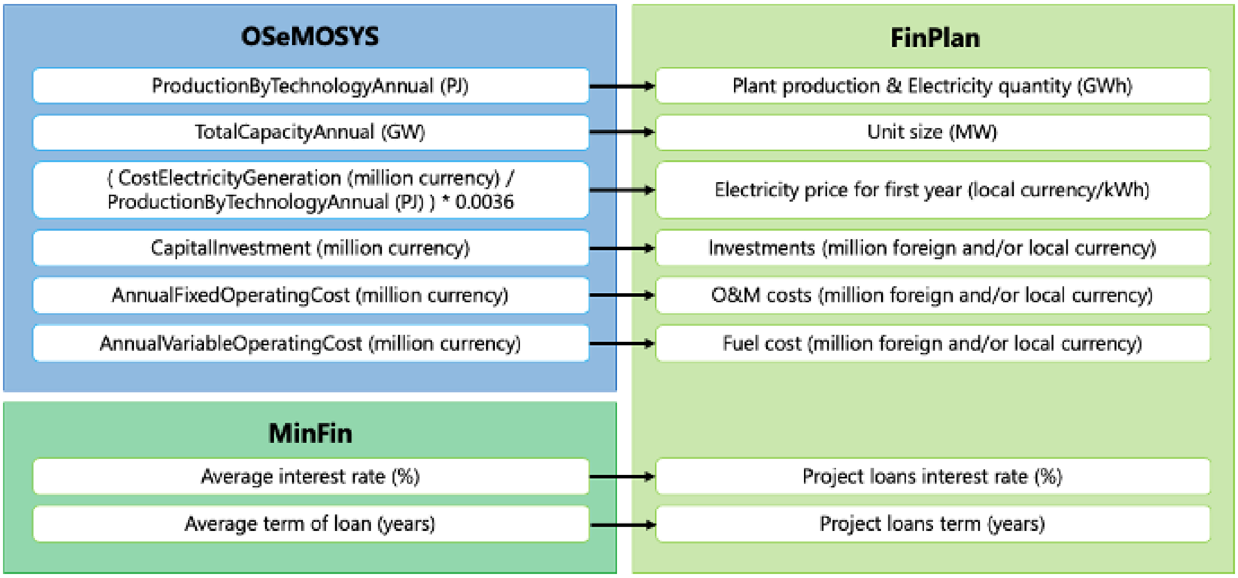

Figure 7: A list of techno-economic outputs from OSeMOSYS and MinFin that can be used as input data for FinPlan. As FinPlan has fixed units, calculations may need to be done to ensure consistency of values from OSeMOSYS to FinPlan.

3. Future Iterations

Future iterations of this work include incorporating four or more tools. These tools are: (1) Open Source Spatial Electrification Tool (OnSSET), an open-source framework that one can use to conduct geospatial electrification analyses [16]; (2) Open Source Spatial Clean Cooking Tool (OnSTOVE), an open-source spatial tool comparing the relative potential of different cookstoves on the basis of their costs and benefits [17]; (3) Electricity Planning Model, a tool used for undertaking least-cost planning purposes of the power sector only [18]; and (4) Fossil Fuel Retirement Model (FFRM), a tool that enables the user to estimate the cost of compensating investors for early withdrawal of fossil fuel power plants [19]. Figure 8 displays the possible linkage of the tools within the analytical workflow.

As mentioned in Section 2.4, the script to collect OSeMOSYS data outputs for interactive visualization via ambition levers on an adapted Carbon Calculator platform is currently being developed. Future work would also include creating a script linking all the tools as mentioned in this article together to automate the data-to-deal process for faster analysis.

Ethics Statements

Not applicable.

Declaration of Competing Interests

The authors declare that they have no known competing financial interests or personal relationships that have or could be perceived to have influenced the work reported in this article.

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CRediT authorship contribution statement

Naomi Tan: Conceptualization, Methodology, Validation, Resources, Writing - Original Draft, Visualization, Project Administration. **Ioannis Vrochidis:** Conceptualization, Methodology, Software, Validation, Resources, Writing - Original Draft. **Hannah Luscombe:** Conceptualization, Methodology, Writing - Original Draft. **Emma Richardson:** Conceptualization, Methodology, Writing - Original Draft. **Leigh Martindale:** Conceptualization, Methodology,

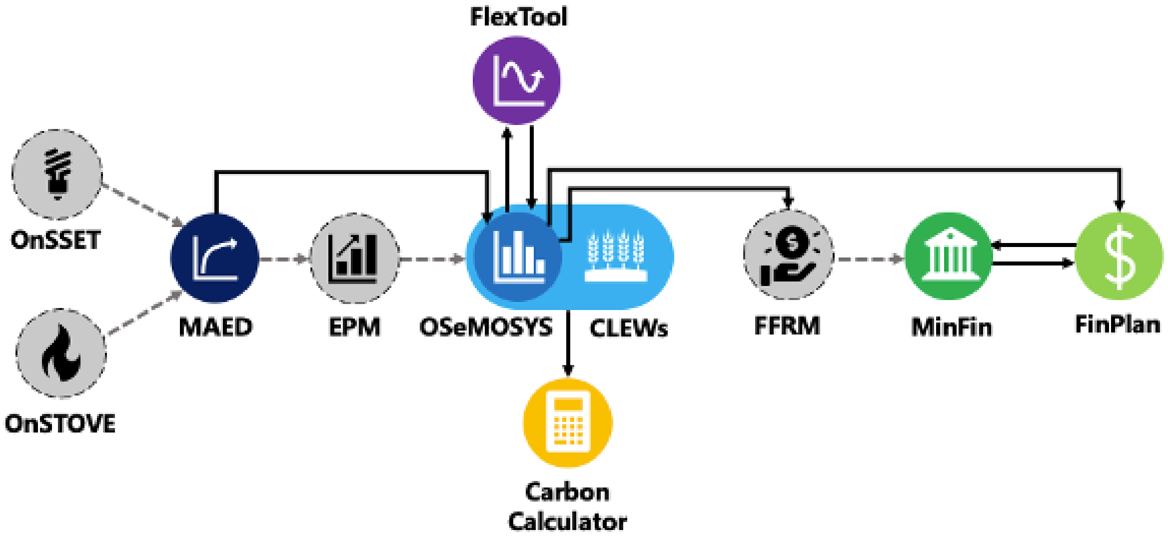

Figure 8: Potential soft-linking of additional tools including OnSSET, OnSTOVE, EPM, and FFRM.

Writing - Original Draft. **Kane Alexander:** Conceptualization, Methodology, Writing - Original Draft. **Vivien Foster:** Conceptualization, Writing - Review & Editing, Supervision. **Mark Howells:** Conceptualization, Writing - Review & Editing, Supervision. **John Harrison:** Conceptualization, Writing - Review & Editing, Supervision.

References

[1] Jaramillo M, Quirs-Torts J, Vogt-Schilb A, Money A, Howells M. Data-to-deal (d2d): Open data and modelling of long term strategies to financial resource mobilization-the case of costa rica 2023;.

[2] International Atomic Energy Agency. Iaea tools and methodologies for energy system planning and nuclear energy system assessments. Tech. Rep.; International Atomic Energy Agency; 2009.

[3] Kanté M, Li Y, Deng S. Scenarios analysis on electric power planning based on multi-scale forecast: A case study of taoussa, mali from 2020 to 2035. Energies 2021;14(24):8515.

[4] Howells M, Rogner H, Strachan N, Heaps C, Huntington H, Kypreos S, et al. Osemosys: the open source energy modeling system: an introduction to its ethos, structure and development. Energy Policy 2011;39(10):5850–70.

[5] Tan N, Harrison J, Howells M, Yeganyan R. Techno-economic data and assumptions for long-term energy systems modelling in viet nam. Data in Brief 2023;46:108836.

[6] Taibi E, Nikolakakis T, Gutierrez L, Fernandez C, Kiviluoma J, Rissanen S, et al. Power system flexibility for the energy transition: Part 2, irena flextool methodology. Tech. Rep.; International Renewable Energy Agency; 2018.

[7] Taibi E, Fernandez C, Gutierrez L, Kiviluoma J, Lindroos TJ. Colombia power system flexibility assessment: Irena flextool case study 2018;.

[8] Howells M, Hermann S, Welsch M, Bazilian M, Segerström R, Alfstad T, et al. Integrated analysis of climate change, land-use, energy and water strategies. Nature Climate Change 2013;3(7):621–6.

[9] United Kingdom Government Department for Business, Energy Industrial Strategy. Mackay carbon calculator. 2023. Accessed: Sep 14 2023. `https://mackaycarboncalculator.beis.gov.uk/overview/emissions-and-primary-energy-consumption`.

[10] Ministry of Energy Kenya. Kcert 2050 carbon calculator. 2023. Accessed Sep 14 2023. `https://kcert.ilabafrica.ac.ke/`.

[11] Ministry of Industry and Trade Viet Nam. Viet nam 2050 calculator. 2023. Accessed Sep 14 2023. `https://vn2050calculator.tietkiemnangluong.com.vn/pathways`.

[12] Shafiqul IM, Bhuiyan TH. Assessment of costs of nuclear power in bangladesh. Nuclear Energy and Technology 2020;6(3):181–94.

[13] Tan N, Ambunda R, Medimorec N, Cortez A, Krapp A, Maxwell E. Transport starter data kit. Zenodo 2023;doi:`10.5281/zenodo.8116419`.

[14] Martindale L, Cannone C, Niet T, Hodgkins R, Alexander K, Howells M. Empowering tomorrow's problem solvers: Nexus thinking and clews modelling as a pedagogical approach to wicked problems. Energies 2023;16(14):5539.

[15] Ramos EP, Howells M, Sridharan V, Engström RE, Taliotis C, Mentis D, et al. The climate, land, energy, and water systems (clews) framework: a retrospective of activities and advances to 2019. Environmental Research Letters 2021;16(3):033003.

[16] Mentis D, Howells M, Rogner H, Korkovelos A, Arderne C, Zepeda E, et al. Lighting the world: the first application of an open source, spatial electrification tool (onsset) on sub-saharan africa. Environmental Research Letters 2017;12(8):085003.

[17] Khavari B, Ramirez C, Jeuland M, Fuso Nerini F. A geospatial approach to understanding clean cooking challenges in sub-saharan africa. Nature Sustainability 2023;6(4):447–57.

[18] Chattopadhyay D, de Sisternes F, Oguah SKE. World bank electricity planning model (epm): Mathematical formulation. Unpublished Report, World Bank, Washington, DC 2018;.

[19] Suski A, Hong L, Chattopadhyay D. Modeling coal plant stranded costs for decarbonization pathway analyses. Energy for Sustainable Development 2022;71:480–9.

A. Appendix

A.1. Reference Energy Systems

Figures 9, 10, 11, 12 displays an example RES diagram that a user can adopt, adapt, and apply to translate MAED outputs as OSeMOSYS inputs.

A.2. Technology Naming Conventions and Descriptions

The naming conventions and descriptions of the CLEWs technologies as shown in Figure 5 are listed in Table A.2.

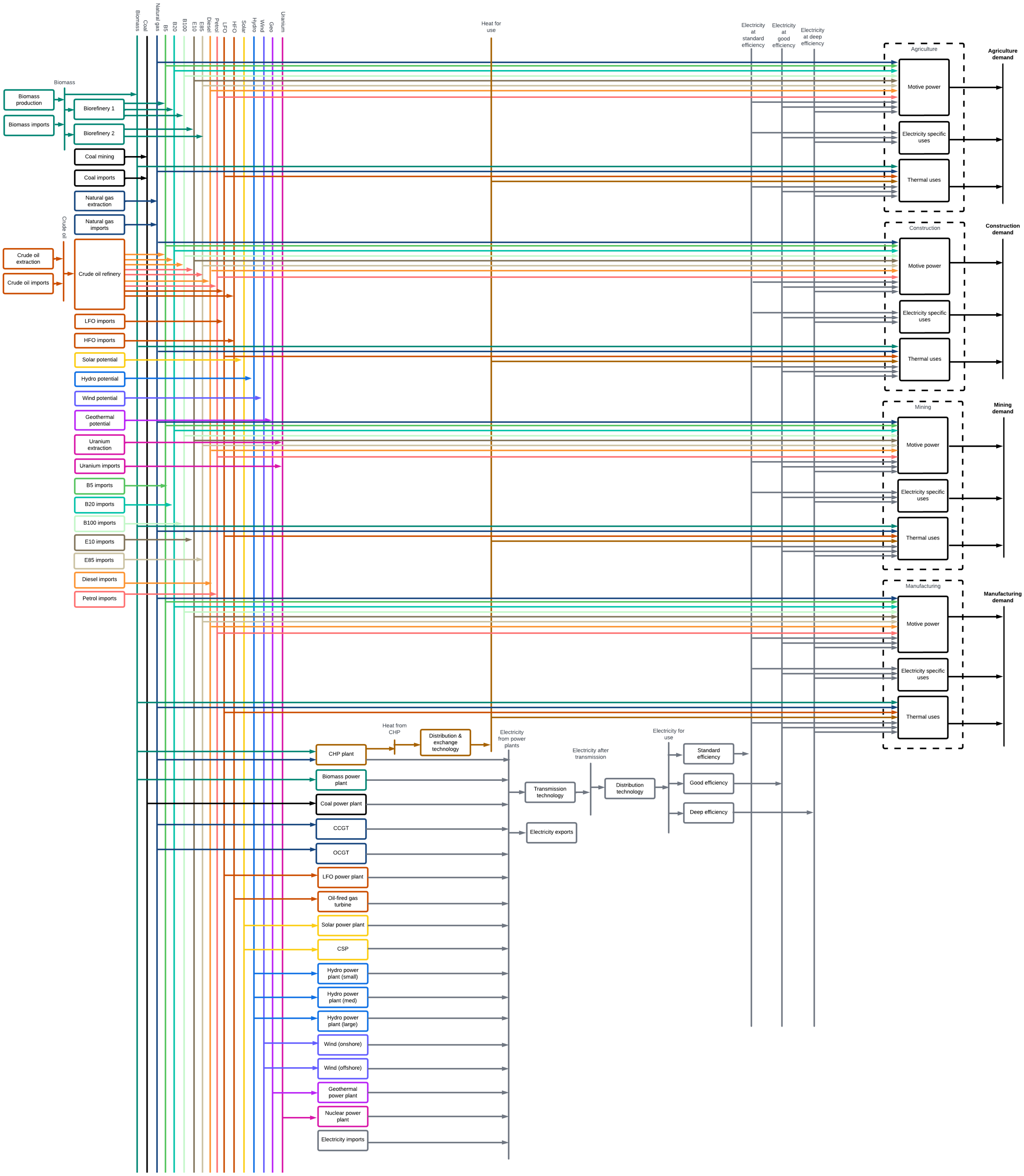

Figure 9: An example RES diagram for the industry sector with the necessary demands, technologies, and fuel types to represent MAED outputs. Note that these commodities and consumption technology may differ based on what the user has defined in MAED.

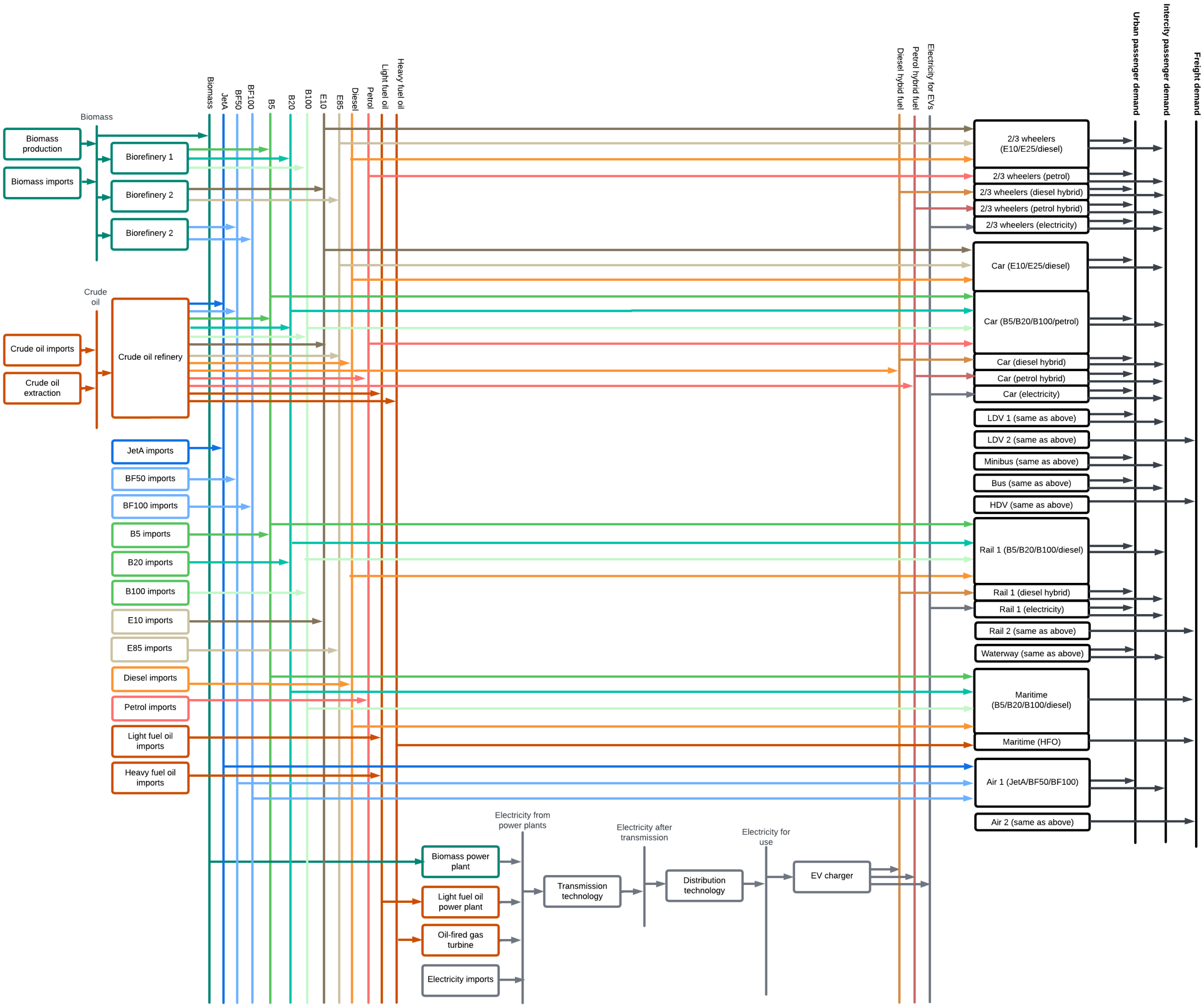

Figure 10: An example RES diagram for the transport sector with the necessary demands, technologies, and fuel types to represent MAED outputs. Note that these commodities and consumption technology may differ based on what the user has defined in MAED.

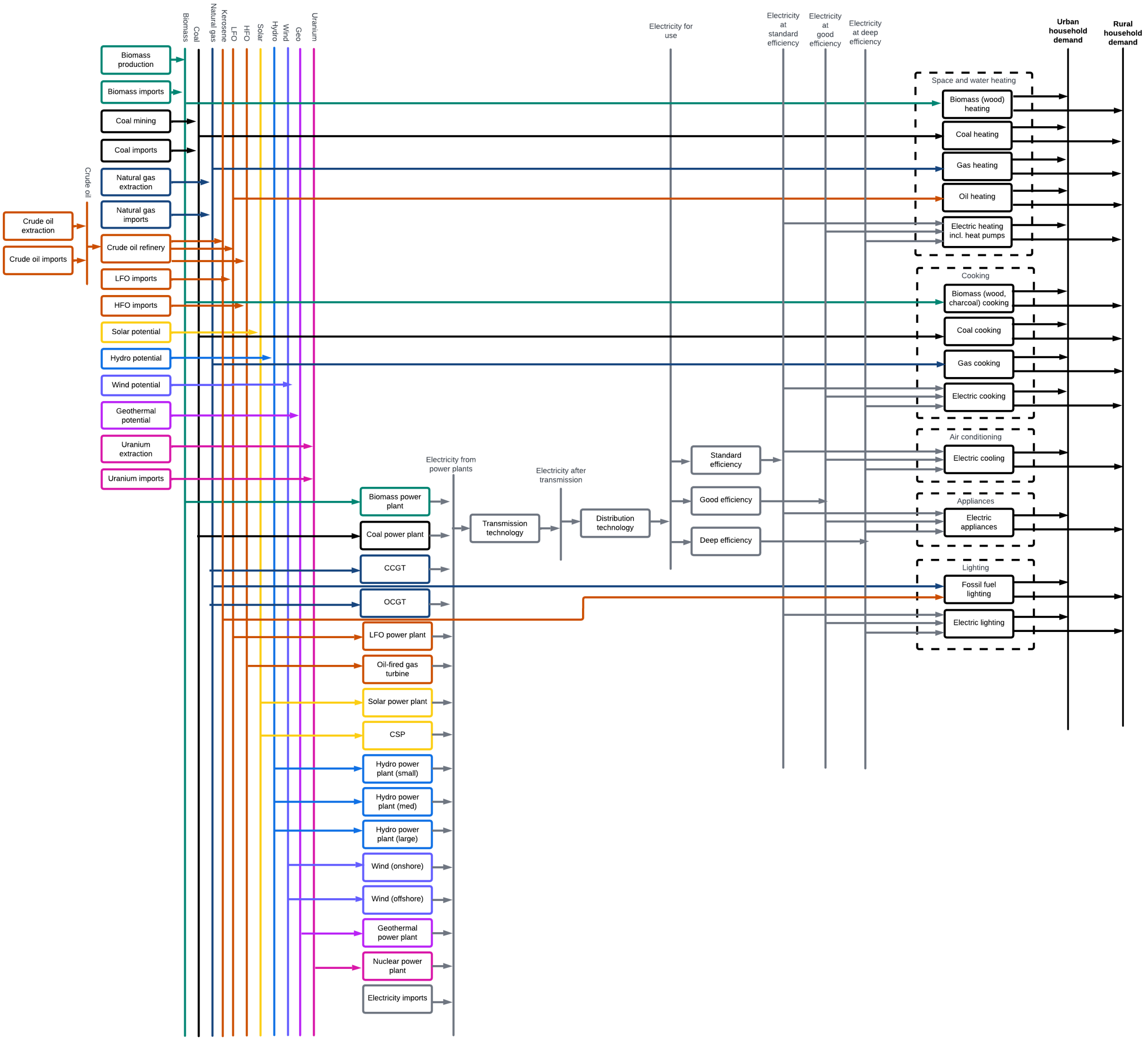

Figure 11: An example RES diagram for the household sector with the necessary demands, technologies, and fuel types to represent MAED outputs. Note that these commodities and consumption technology may differ based on what the user has defined in MAED.

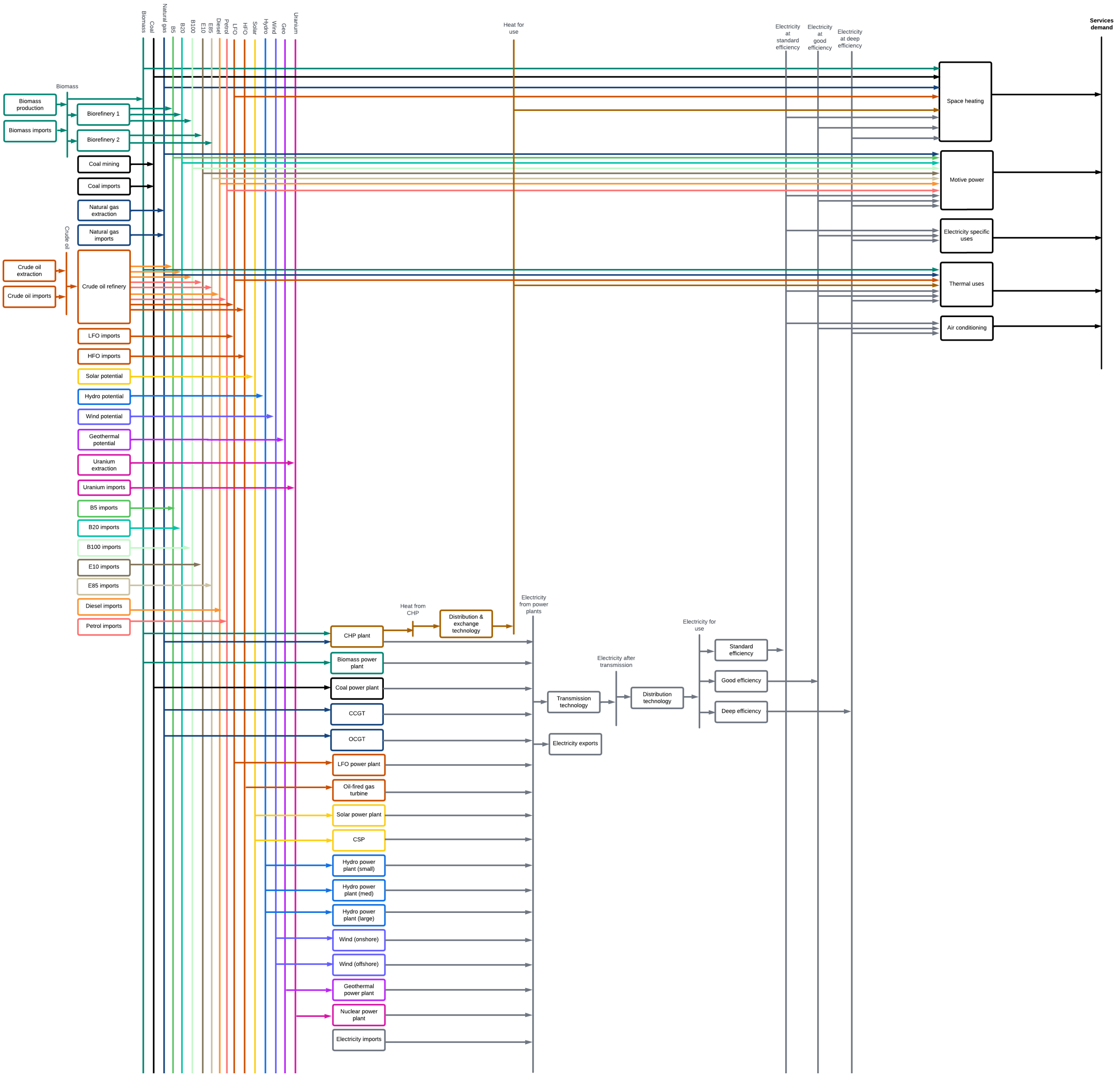

Figure 12: An example RES diagram for the services sector with the necessary demands, technologies, and fuel types to represent MAED outputs. Note that these commodities and consumption technology may differ based on what the user has defined in MAED.

Table 1
CLEWs Naming Conventions and Descriptions

Name	Description
MINLND	Land resource
LNDMAIHR	Land for rainfed maize cultivation
LNDRICHR	Land for rainfed rice cultivation
LNDMAIHI	Land for irrigated maize cultivation
LNDRICHI	Land for irrigated rice cultivation
LNDFOR	Land representing forests
LNDBLT	Land representing built up land
LNDWAT	Land representing water bodies
MINPRC	Precipitation water resource
MINGAS	Gas extraction
MINCOA	Coal extraction
MINHYD	Hydro resource for power
MINSOL	Solar resource for power
MINWND	Wind resource for power
PWRGAS	Gas power plant
PWRCOA	Coal power plant
PWRHYD	Hydropower plant
PWRSOL	Solar photovoltaic
PWRWND	Wind turbines
PWRTRN	Power transmission
DEMAGRDSL	Diesel used in agriculture sector
DEMAGRSURWAT	Surface water supply for agriculture
DEMAGRGWTWAT	Groundwater supply for agriculture
DEMPWRSURWAT	Surface water supply for power plants
DEMPWRGWTWAT	Groundwater supply for power plants
DEMPUBSURWAT	Surface water supply for public supply
DEMPUBGWTWAT	Groundwater supply for power plants
DEMTRABIO	Biofuel for transport
LND	Land
CRPMAI	Maize
CRPRIC	Rice
WTRPRC	Precipitation
AGRWAT	Agricultural Water
WTREVT	Evapotranspiration
WTRGWT	Groundwater
WTRSUR	Surface water
PWRWAT	Water for cooling power plants
PUBWAT	Public water
GAS	Gas
COA	Coal
HYD	Hydro
SOL	Solar
WND	Wind
ELC001	Electricity after transmission and distribution
ELC002	Electricity for final use
AGRDSL	Agricultural diesel
LFOR	Forests
LBLT	Built up land
LWAT	Water bodies
TRABIO	Biofuel for transport