



**TRIBHUVAN UNIVERSITY
INSTITUTE OF ENGINEERING
PULCHOWK CAMPUS**

THESIS NO: M-160-MSESP-2019-2023

**CLIMATE, LAND, ENERGY AND WATER SYSTEM NEXUS OPTIMIZATION
MODELLING FOR NEPAL**

by

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A THESIS

**SUBMITTED TO DEPARTMENT OF MECHANICAL AND
AEROSPACE ENGINEERING IN PARTIAL FULFILLMENT OF THE
REQUIREMENTS FOR THE DEGREE OF MASTER OF SCIENCE IN
ENERGY SYSTEM PLANNING AND MANAGEMENT**

**DEPARTMENT OF MECHANICAL AND AEROSPACE ENGINEERING
PULCHOWK, LALITPUR, NEPAL**

APRIL, 2023

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ABSTRACT

This thesis introduces the amazing CLEWs Nepal model - a powerful tool that sheds light on the intricate interplay between climate policies and crucial resources like land, energy, and water. With more and more countries taking bold steps to combat climate change, it's crucial to understand the ripple effects of such decisions on other sectors. That's where CLEWs come in, providing decision-makers with valuable insights into the trade-offs and synergies involved in various climate policies.

This thesis examines the impact of the increasing global demand for power on greenhouse gas emissions, water usage, and hydropower production in Nepal. The study projects that by 2050, the country will need to generate 9 GW of power, which can be mostly fulfilled by hydropower. However, this increase in power production will result in a significant rise in CO₂ emissions, particularly from the transport and biomass sectors. To mitigate the impact of this growth, the study recommends improving irrigated farming and forest conservation. The implementation of the Nationally Determined Contributions (NDC) can also contribute to reducing CO₂ emissions and increasing hydropower production. Under NDC scenario, the equivalent gross energy demand decreases by 135 PJ by 2030 whereas the power production rises by 3.5 GW including hydro and solar. Similarly, the import of fossil fuel will reduce by 40 PJ by 2030 and 400 PJ by 2050 A.D. The study further recommends adopting a sustainable nexus approach to energy planning, with a focus on land, water, and climate. It also suggests adopting subsidies for electric cooking and vehicles to increase electricity demand. Finally, the study recommends modeling for land energy and crop trade to ensure trade and food security and exploring the potential for electricity export. Adopting these recommendations can ensure sustainable development and management of resources in Nepal.

ACKNOWLEDGEMENT

I would like to express my sincere gratitude to my supervisors Asso. Prof. Dr. Hari Bahadur Darlami and Asso. Prof. Dr. Ajay Kumar Jha for their valuable advice, suggestions, guidelines, and cooperative supervision which have been the driving factors for the completion of this thesis work.

I am also very grateful to Dr. Shree Raj Shakya for providing necessary guidelines and suggestions and linkages in getting familiar with the modelling tool. More importantly, I would like to thank Professor Dr. Taco Niet of Simon Fraser University, Canada who gave me the idea and materials to start developing the model for Nepal.

I am also thankful to all the members of the Institute of Engineering, Pulchowk Campus, Tribhuvan University. I would like to convey special thanks to Assistant Director of AEPC Dr. Laxman Ghimire and Managing Director of Rastriya Urja Dakshata Kendra Pvt. Ltd. for helping and encouraging me while conducting this thesis.

I am highly indebted to the Department of Mechanical and Aerospace Engineering for providing me with the necessary materials and platform for conducting the thesis. I would like to express sincere thanks to the lecturer, faculty staff and administration for their support and coordination as well.

I truly appreciate the inspiration given by my family and friends for generously motivating me to reach the goal of completing this thesis.

Finally, I would like to thank all who directly and indirectly helped doing this thesis.

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LIST OF ABBREVIATIONS

| | |
|----------|--|
| BAU | Business as Usual |
| CLEWs | Climate land Energy Water System |
| FAO | Food and Agriculture Organization |
| GAEZ | Global Agro Ecological Zones |
| GNU | GNU's Not Unix |
| IEA | International Energy Agency |
| IPP | Independent Power Producer |
| ISO | International Organization for Standardization |
| LPG | Liquified Petroleum Gas |
| MoEWRI | Ministry of Energy Water Resources and Irrigation |
| MoF | Ministry of Finance |
| Momani | Model management infrastructures |
| NDC | Nationally Determined Contribution |
| NEA | Nepal Electricity Authority |
| NPC | National Planning Commission |
| OSeMOSYS | Open-Source Energy Modelling System |
| RES | Reference Energy System |
| SDG | Sustainable Development Goals |
| UN | United Nation |
| UNDESA | United Nations Department of Economic and Social Affairs |

CHAPTER ONE: INTRODUCTION

1.1 Background

Food, energy, land, and water are all essential components for human sustenance and are highly interrelated. Understanding these interconnections can be aided by the creation of the climate, land, energy, and water systems (CLEWS) modelling framework. For each of the three resources and their integrated characteristics, the CLEWS approach uses current well-tested assessment procedures. It can reveal linkages between policies for the Sustainable Development Goals (SDGs) and nationally specified contributions under the Sustainable Development Goals (SDGs) on climate change as per the Paris agreement.

Food, energy, and water security are essential for human survival; hence they are at the center of sustainable development. The three have particularly strong ties, emphasizing the importance of cross-sectoral methods based on integrated assessments. Furthermore, billions of people do not have access to modern electricity, food, or water.

In developing countries, the bottom billion people do not have access to necessities, while lower middle-income people find themselves spending a big percentage of their earnings on these basic needs.

All United Nations members committed in 2015 to the 2030 Agenda for Sustainable Development, which is a historic international commitment to responsible growth, shared prosperity, and poverty reduction. Its goals are to enhance people's living situations, safeguard the environment, and promote peace and inclusive society. This bold vision necessitates strong governance and well-crafted public policies to efficiently balance each country's economic, social, and environmental priorities. The 17 Sustainable Development Goals are at the heart of the agenda.

Providing food, energy, and water security to a world that is expanding in size and wealth is a key component of the 2030 agenda (Johnston, 2016). These goals must be reached while safeguarding natural resources and mitigating and managing climate change's effects. These variables, taken collectively, provide significant obstacles to achieving long-term development. These challenges are addressed by four targets in the 2030 Agenda.

SDG 2: Reduce hunger, increase food security and nutrition, and promote sustainable

agriculture.

SDG6: Ensure everyone has access to cheap, reliable, sustainable, and modern water and sanitation.

SDG7: Ensure everyone has access to affordable, reliable, sustainable, and modern energy. SDG13: Take immediate action to mitigate climate change and its effects.

These objectives are linked and interconnected challenges. Any progress made on one has the potential to affect the others. The success or accomplishment of one can have ramifications for the others.

As a result, the interconnection of development concerns has a far stronger impact on how decision-making and policy-making procedures should be carried out. For discovering the nexus of these characteristics, there needs to be a lot of detailed and consistent investigation and modelling. Any progress made on one has the potential to affect the others. The success or accomplishment of one can have ramifications for the others.

As a result, the interconnection of development concerns has a far stronger impact on how decision-making and policy-making procedures should be carried out. For discovering the nexus of these characteristics, there needs to be a lot of detailed and consistent investigation and modelling.

Climate, land, Energy and Water system modelling framework (CLEWs) is best suited for finding out the interlinkage between these parameters and provide support in policy and decision making.

CLEWs is a tool for considering food, energy, and water security challenges at the same time. It allows you to study and assess the interconnections between energy, water, and agriculture systems, as well as their implications and sensitivity to climate change. It is intended to assist in identifying and quantifying trade-offs and synergies that may occur when pursuing policy goals in multiple areas at the same time. As a result, it can serve as an analytical foundation for a logical and consistent strategy and policy-making process.

CLEWs can be used to discover pressure points and reveal synergies and trade-offs to achieve development goals by comparing alternative technologies and value chains. It can aid in the analysis of policy decisions on topics including greenhouse gas reductions,

water competition, climate resilience, land use change, and agriculture modernization. The CLEWs model includes a method of assessing sectoral development strategies and their interdependencies by running land, energy, and water models in concurrently taking care of their interaction in climatic behaviors. The models are soft linked (i.e., modelling results are communicated between sectoral models), and scenarios that are consistent across sectors are developed in an iterative process.

The CLEWs model is developed in MOMANI and then runs in OSeMOSYS which is a cloud model running platform. The visualization and comparison from the output will be the guiding factor for further improvement and informing policy makers to investigate the best suited changes to plan for a sustainable future.

The CLEWS platform, which was utilized in the creation of this model, is intended to examine connections between the systems of the climate, land (food), energy, and water. The framework incorporates some elements of the nexus concept because it was built using the UN's sustainable development (SD) paradigm (Country, 2015). An open-source modeling framework called CLEWS was developed to make use of current, tried-and-true methods for evaluating energy, water, and land (agricultural) resources, as well as climate data, to provide an integrated study. The CLEWS platform stands out as a distinct tool for assessing policymakers' advancements towards Paris Agreement objectives because it was developed in conjunction with the United Nations Department of Economic and Social Affairs (UNDESA) and the United Nations Development Program (UNDP) to evaluate policies aligned with UN sustainable development goals. (Country, 2015). The CLEWS platform is currently being used by a number of finished and ongoing projects to examine various policy-related topics across a range of special and temporal scales, as well as between interactions involving two or more resources (ARIANPOO, SINGH, WRIGHT, & NIET, 2021).

More than 90% of GHG emissions are attributed to energy, agriculture, and land use change (van Vuuren et al., 2017). Bioenergy is using an increasing amount of cropland. Water withdrawals from agriculture and the energy sector account for 90% of global water withdrawals (“AQUASTAT | Land & Water | Food and Agriculture Organization of the United Nations | Land & Water | Food and Agriculture Organization of the United Nations,” 2016)

Water treatment and supply account for about 4% of global electricity use. Crop

cultivation uses 4% to 5% of total energy. Moderate to severe food insecurity affects 25% of the adult population worldwide. A quarter of the world's population lives in areas where there is a lot of water scarcity. 35 percent of the world's population does not have access to safe and clean cooking energy(Johnston, 2016). And under all of these, the world is not on course to reach the Paris Agreement on Climate Change, which was signed in 2015.

It is projected that by 2050, the expansion of arable land worldwide will be restricted to approximately 70 million hectares, which is less than 5% of the current arable land. Developing countries, mainly in Sub-Saharan Africa and Latin America, are expected to account for approximately 120 million hectares (12%) of the expansion. America, offset by a decline of about 50 million hectares (8%) in developed countries (“AQUASTAT | Land & Water | Food and Agriculture Organization of the United Nations | Land & Water | Food and Agriculture Organization of the United Nations,” n.d.)

Nepal aims to ensure that 15 percent of overall energy demand is met by clean energy sources and 25% of families use electric stoves as their principal means of cooking by 2030 (GoN, 2020).

Similarly, Nepal has targeted increase in clean energy generation from around 1,400 MW to 15,000 MW by 2030, with 5-10% coming from mini and micro hydro power, solar, wind, and bioenergy. Among these, 5,000 MW is a firm aim. The rest is reliant on the international community's contribution of funds(GoN, 2020). Nepal aims in improving self-sufficiency in food grains will result in a 0-5 percent trade surplus by 2030. Also, Agricultural productivity will have improved to 4 Metric Tons (MT) per hectare by 2024, up from 3.1 MT per hectare in 2019 (NPC, 2019).

From 48 percent in 2019 to 80 percent in 2024, the number of households with basic food security will have increased and also from 8.9% in 2019 to 4% in 2024, the population deprived of the daily minimum calorie intake will have decreased(NPC, 2019)Between 2019 and 2024, an extra 300,000 hectares of land will be irrigated and the yearly timber production will be boosted from 19.4 million cubic feet in 2019 to at least 30 million cubic feet by 2024, making Nepal self- sufficient in timber(NPC, 2019).

These targets can only be met if there is a combined modelling done among these goals to find out the nexus connection between these so that there is a check and balance

situation to mitigate adverse impact and combat with the ongoing climate change. CLEWs modelling is a suitable approach that this research tries to build. This is just a preliminary approach in building a baseline scenario for the nexus of food water energy and climate for Nepal. Further scenarios can be built which will open doors for further research in these fields.

1.2 Problem Statement

The most pressing issue of our day is climate change, which is causing global temperatures to rise, an increase in the frequency of natural disasters, and a shortage of natural resources. Due to the effects of climate change, urbanization, and population expansion, it is anticipated that by 2050, the world's demands for water, food, and energy would have increased by nearly 50% (Khan, Linares, & García-González, 2017). Accelerating the decarbonization of the energy system is necessary to combat climate change. Ambitious energy decarbonization strategies are being adopted by an increasing number of countries, regions, and municipalities. Despite the increasing adoption of energy transition policies, only a limited number of studies have explored their potential impact on water resources, natural and agricultural areas. Additionally, there is a lack of understanding on how changes in these areas could influence the cost and effectiveness of energy policies in the long run.

Talking about Nepal, Nepal is developing, and the electricity production is going to be more than demand in few years' times. There is an immediate plan required on how the country is going to utilize its excess electricity. There can be several areas explored like going towards EV, going towards electric cooking, establishing medium and large-scale industries.

In the same way, the population is increasing day by day and the area available for food cultivation is limited. There is a great need for transition in our farming system to produce more food with limited land resources available.

Similarly, the dependency on fossil fuel for transport, industry and cooking has posted a great threat in climate change due to the production of excessive greenhouse gases. A proper tackling strategy needs to be adopted in time for the mitigation of upcoming dangerous situations.

To combat these issues and for long term energy expansion, Nepal also has posted some ambitious target. But there is no proper strategies on how the country is going to achieve

the target. CLEWs modelling will create a baseline scenario for achieving various policies target.

1.3 Research Objective

Main objective of the study is to develop Reference Energy System for Climate, Land, Energy and Water nexus and optimize those to build CLEWs model for Nepal.

Specific objectives of the study are:

- To generate long term energy expansion model for Nepal through optimization
- To utilize the capabilities of MoManI as a model management infrastructure to build complex models, and to utilize OSeMOSYS for visualizing the results of those models
- To find out the energy mix scenario for fulfilling the energy demand till 2050 AD
- To forecast the greenhouse gas emission till 2050 AD and look for alternative ways to reduce the emission

1.4 Underlying Assumption

The OSeMOSYS energy modeling framework is expanded in the CLEWS Modelling framework (Ramos et al., 2021). A bottom-up modeling framework called OSeMOSYS was created to offer user-defined regions long-term cost optimization for their energy systems. In this context, "modelling framework" refers to software that creates certain models by filling them with user-defined data" (Gardumi et al., 2018). OSeMOSYS is a capacity growth model that utilizes linear programming. It determines the optimal mix of power generation technologies required to meet a given trajectory of exogenously determined demands, while considering resource and policy constraints

The energy infrastructure of OSeMOSYS and its predecessor, CLEWS, can be easily customized and adapted to meet the specific needs of a given analysis. The model's design utilizes a series of functional component "blocks" that allow for this flexibility and versatility. To create a unique model, a set of the functional building pieces is combined " (Howells et al., 2011). Each of the component blocks in the model contains a self-contained set of equations and variables that can be incorporated into the fundamental code of the model, enabling it to generate specific insights for the user-design inquiry. (Gardumi et al., 2018). Each component block in the model has three layers of abstraction for user communication: a simple English description, an algebraic

formulation, and the block's code implementation. This unique modeling framework is user-friendly, easy to learn, and accessible to a broad range of audiences. The design approach used to create the energy infrastructure of OSeMOSYS can also be extended to include other nexus elements in addition to the energy system, using the same process applied in the creation of the CLEWS framework. It is important to note that the CLEWS framework is not inherently biased towards any specific system, and users have the ability to customize their analysis by specifying the goals and parameters of each case study. (Ramos et al., 2021).

Initially, the energy and land systems were developed independently based on a Clustering approach, and then the connections between each pair of systems were established to create the model. The interactions between the water and energy systems were specified, such as the amount of water needed to produce energy from each source, and the amount of energy required for operating water treatment facilities. Similarly, the relationship between the energy and land systems was determined by considering the amount of energy needed for agricultural activities like water pumping and agricultural operation. Later, the model was updated to include the activity ratio of CO₂ emissions generated by each activity.

While the model is still in its preliminary phase, it can be made policy-driven, like other models created in CLEWS and OSeMOSYS. Analysis begins with each system, based on user-defined variables, when a scenario is run. This phase involves examining resource availability, demand trends for energy, agricultural goods, and water, as well as regulatory restrictions within each system to understand the limits, drivers, and pressure points for each system. The model then evaluates the trade-offs and synergies caused by each policy by considering the points at which each system interacts with the others. The model provides a least-cost technology mix (optimization) to meet power demand during the modeling period, along with total CO₂eq emissions produced by the system.

CHAPTER TWO: LITERATURE REVIEW

2.1 CLEWs overview

The Climate, Land (Food), Energy and Water systems approach (CLEWs) is designed to explore the connections between resource systems, identify pressure points, and maximize synergies while minimizing trade-offs.

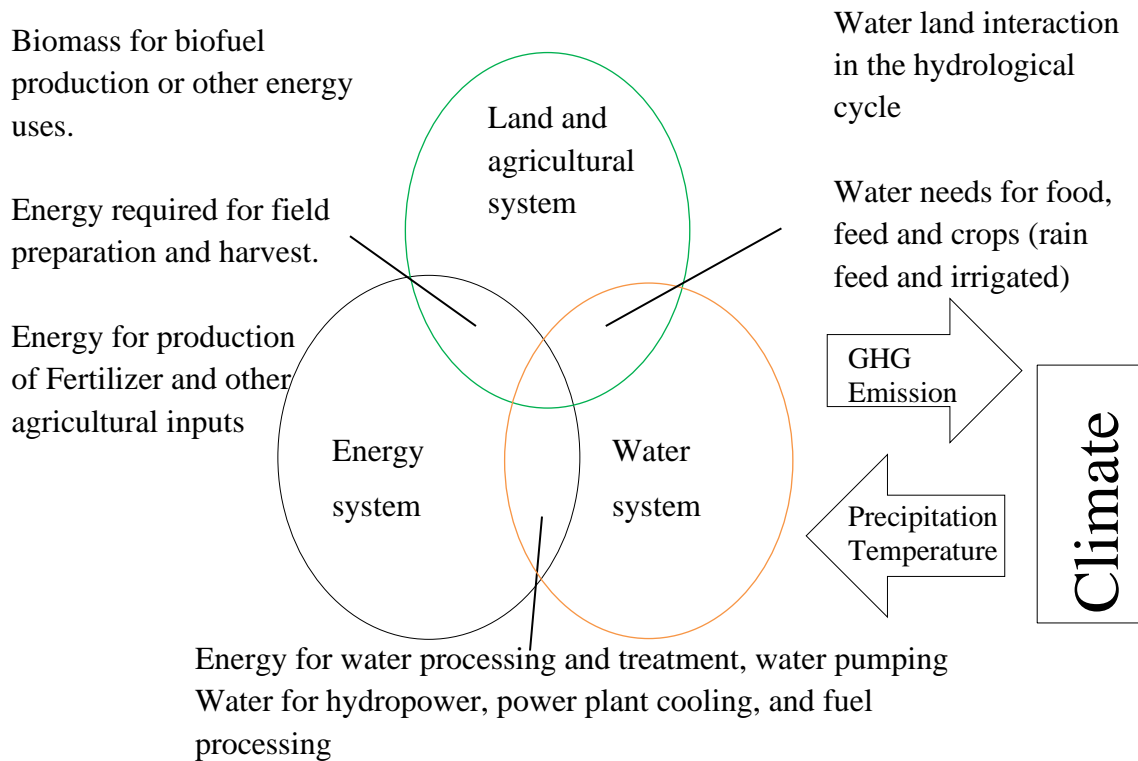


Figure 2.1: conceptual CLEWs diagram

Integrated assessments can be conducted at different levels of complexity, including:

- Accounting frameworks
- Sectoral models for water, energy, and land use, with soft linking of tools in an iterative process

- A single modelling tool that considers multiple cross- and inter-systems' interactions. These models can be used to investigate issues related to the relevant nexus interactions (Howells et al., 2011).

2.2 Clewsy

Clewsy is a software tool that offers a command-line interface to construct CLEWs models using OSeMOSYS. It is coded in Python.

2.3 MoMani

MOMANI stands for Model Management Infrastructure. Effective energy planning is a key element in developing national sustainable development policies. To aid countries in enhancing their energy planning capacities, an open, accessible, transferable and efficient modeling package is crucial. After analyzing UNDESA's capacity development in pilot countries, the Model Management Infrastructure (MoMani) was developed to run the open-source energy modeling program OSeMOSYS. As a result, MoMani aids in giving energy planners the resources needed to build models, investigate situations, and visualize outcomes. MoMani is an open-source browser-based interface for modelling energy systems. Its innovative structure enables teams to work together concurrently from different parts of the world and is accessible to all types of users, including academics, policymakers, and energy planners.

2.4 OSeMOSYS

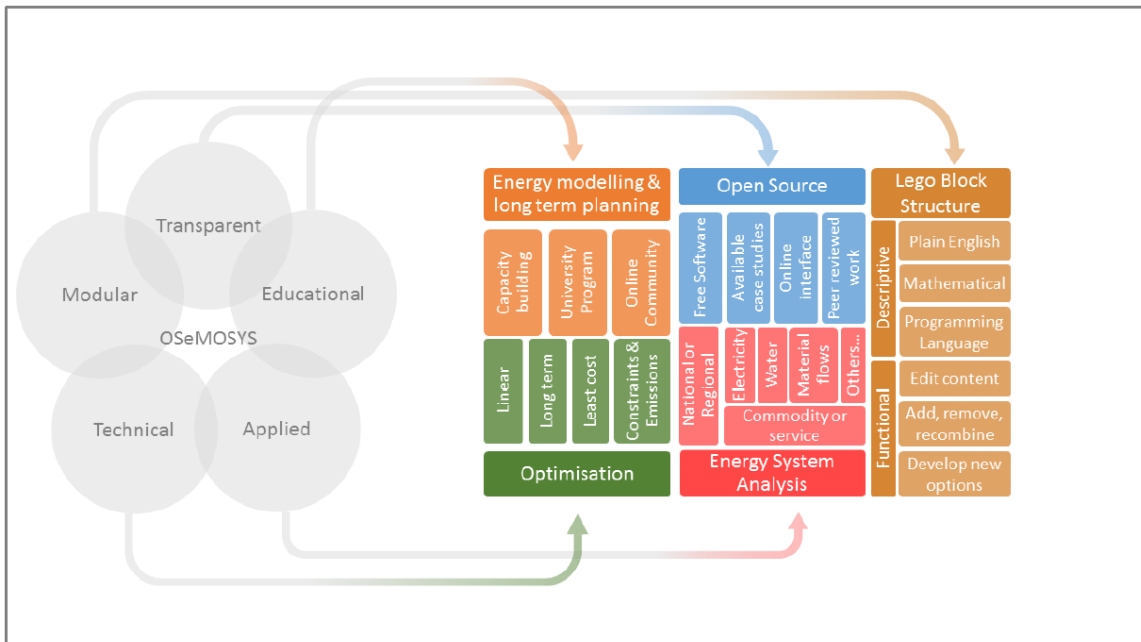
The OSeMOSYS tool is made to help with the creation of regional, national, and local energy strategies. It can include all energy sectors or just certain ones, like heat, electricity, and transportation. In a deterministic linear optimization model, the total discounted costs are minimized. For some tasks, such as the optimization of discontinuous power plant capacity increases, mixed integer programming may be used (Howells et al., 2011).

The cost of energy-producing technologies to meet an exogenously set demand is what drives the model (s). This group of technologies makes use of a variety of resources, each of which has advantages and disadvantages. Additionally, technical limitations, economic realities, or environmental goals could be imposed by policy scenarios. The standard configuration of OSeMOSYS makes the same assumptions as most long-term optimization

models, including perfect foresight and perfect competition in the energy markets.

The initial code of OSeMOSYS is composed of 700 lines of text written in GNU MathProg, a mathematical programming language that is easy to understand for users of all proficiency levels, including those without expertise in linear programming. Additional parallel versions of the code have also been developed in Python and GAMS to enhance compatibility with the various user and programming communities. The models can be converted into matrices using the free source solver GLPK, which can also locate the best solution and report the numerical results (OSeMOSYS Documentation Release 0.0.1 KTH-dESA, 2021).

Although OSeMOSYS can be created and run without an interface, multiple user interfaces have been developed and are commonly used for teaching and capacity building purposes. One such interface is the Model Management Infrastructure (MoManI), which is freely available as an open-source online or desktop version for creating models and visualizing results. Additionally, OSeMOSYS has been integrated into LEAP as a module for calculating supply capacity expansion planning.



(MoMani training manual-KTH DESA)

Figure 2.2: OSeMOSYS Overview Structure of OSeMOSYS

In OSeMOSYS, like in every linear programming, sets parameter and variable are required and they are bound up by some constraints.

2.4.1 Sets

The "sets" in a model define its physical structure, usually without regard to specific scenarios that will be analyzed. These sets determine the time period, time resolution, geographical area, technologies, energy carriers, and other relevant factors that need to be considered in the model. For example, a variable can be defined as "variablename [y]" if it is dependent on the "YEAR" set, meaning that it will be calculated for each year specified in the set. The description of each set used in the model is tabulated below results (OSeMOSYS Documentation Release 0.0.1 KTH-dESA, 2021)

Table 2.1: Description of set used in the model

| S. N. | Set | Description |
|-------|----------------|--|
| 1. | Year (y) | Represents the time period covered by the model. It includes all years that need to be considered for the study. |
| 2. | Technology (t) | Refers to any component of the energy system that transforms, utilizes or supplies a commodity. In OSeMOSYS, all system elements are treated as technologies. The modeler can interpret the role of a technology as per the requirements of the study. |
| 3. | Commodity | Refers to any form of energy, energy service, or proxies that enter or exit the technologies. Depending on the analysis needs, these can be aggregated groups, individual flows or artificially separated. |
| 4. | Time Slices | Represents the time resolution of the model. It shows the time division of each modeled year. Common energy systems modeling tools such as MESSAGE, MARKAL, and TIMES, slice the annual demand into representative fractions of the year. |
| 5. | Emission (e) | Refers to any type of emission that can occur from the operation of the defined technologies. For example, |

| S. N. | Set | Description |
|-------|-----------------------|---|
| | | atmospheric emissions of greenhouse gases such as CO ₂ . |
| 6. | Region (r) | Specifies the regions to be modeled such as different countries. For each region, the supply-demand balances for all energy vectors are ensured, including trades with other regions. In some cases, modeling different countries within the same region and differentiating them by creating ad hoc fuels and technologies for each can be computationally convenient. |
| 7. | Mode of Operation (m) | Refers to the different modes of operation that the technologies can have. If a technology can have various input or output fuels and it can select the mix of these fuels, each mix can be treated as a separate mode of operation. For instance, a CHP plant may produce heat in one mode of operation and electricity in another. |

2.4.2 Parameters

Parameters are numerical inputs that are defined by the user and are used in the model. It is common practice to change the values of certain parameters when running multiple scenarios and sensitivity analyses, while the structure of the model and the sets usually remain constant. Each parameter is dependent on the components in one or more sets. For example, the Capital Cost [r, t, y] illustrates that the capital cost is determined by the region (r), the technology (t), and the year (y).

Table 2.2: Parameters used in the model

| Name | Description |
|--------------------------|---|
| Demands | |
| Specified Annual Demand | The total demand for a commodity or energy-service during a specified year, linked to a specific time of use during the year. |
| Specified Demand Profile | The annual fraction of a commodity or energy-service demand that is required in each time slice. The sum of |

| | |
|----------------------------|--|
| | all defined input values should equal 1 for each year. |
| Accumulated Annual Demand | The accumulated demand for a commodity in a specific year. It cannot be defined if the specified annual demand for the same year is already defined, and vice versa. |
| Performances | |
| Capacity To Activity Unit | The conversion factor that relates the energy that would be produced when one unit of capacity is fully utilized in one year. |
| Capacity Factor | The capacity available per each time slice expressed as a fraction of the total installed capacity. It accounts for forced outages. |
| Availability Factor | The maximum time that a technology can run in the whole year, expressed as a fraction of the year. It accounts for planned outages. |
| Operational Life | The useful lifetime of a technology, expressed in years. |
| Residual Capacity | The remaining capacity available from before the modeling period. |
| Input Activity Ratio | The rate of use of a commodity by a technology, expressed as a ratio of the rate of activity. |
| Output Activity Ratio | The rate of commodity output from a technology, expressed as a ratio of the rate of activity. |
| Technology Cost | |
| Capital Cost | The capital investment cost of a technology per unit of capacity. |
| Variable Cost | The cost of a technology for a given mode of operation (variable O&M cost) per unit of activity. |
| Fixed Cost | The fixed O&M cost of a technology per unit of capacity. |
| Capacity Constraints | |
| Capacity Of One Technology | The capacity of one new unit of technology. If the user |

| | |
|--|---|
| Unit | sets this parameter, the related technology will be installed only in batches of the specified capacity, and the problem will turn into a Mixed Integer Linear Problem. |
| Total Annual Max Capacity | The total maximum existing (residual plus cumulatively installed) capacity allowed for a technology in a specified year. |
| Total Annual Min Capacity | The total minimum existing (residual plus cumulatively installed) capacity allowed for a technology in a specified year. |
| Investment Constraints | |
| Total Annual Max Capacity Investment | The maximum capacity of a technology expressed in power units. |
| Total Annual Min Capacity Investment | The minimum capacity of a technology expressed in power units. |
| Activity Constraints | |
| Total Technology Annual Activity Upper Limit | The total maximum level of activity allowed for a technology in one year. |
| Total Technology Annual Lower Limit | The total minimum level of activity allowed for a technology in one year. |
| Total Technology Mode Period Activity Upper Limit | The total maximum level of activity allowed for a technology in the entire modeled period. |
| Total Technology Model Period Activity Lower Limit | The total minimum level of activity allowed for a technology in the entire modeled period. |
| RE Generation target | |
| RE Tag Technology | A binary parameter tagging the renewable technologies that must contribute to reaching the indicated minimum renewable production target. It has a value of 1 for the technologies contributing, 0 otherwise. |
| RE Tag Fuel | A binary parameter tagging the fuels to which the renewable target applies. It has a value of 1 if the target |

| | |
|----------------------------|---|
| | applies, 0 otherwise. |
| RE Min Production Target | The minimum ratio of all renewable commodities tagged in the RE tag Commodity parameter to be produced by the technologies tagged with the RE Technology parameter. |
| Emission | |
| Emission Activity Ratio | The emission factor of a technology per unit of activity, per mode of operation. |
| Emission Penalty | The penalty per unit of emission. |
| Annual Exogenous Emission | A parameter that allows the user to account for additional annual emissions on top of those computed endogenously by the model (e.g., emissions generated |
| Annual Emission Limit | Maximum amount of a specific type of emission that can be generated within the entire modeled region in one year. |
| Mode Period Emission Limit | Maximum limit for the amount of a specific emission that can be produced in the entire modeled region during the modeled period, which is usually one year. |

2.4.3 Variables

The outputs of the code are represented by the variables. The variables are functions of the elements of one or more sets in the same way as the parameters are. To increase processing power at the expense of code readability, OSeMOSYS was developed. Only a few of the variables are computed in this version. The range of a few variables, when reasonable to reduce the size of the solution space and, consequently, the computational complexity, has been confined to be positive effort.

2.4.4 Functions

The OSeMOSYS code is designed with modular blocks of equations, comprising multiple constraints and one objective function. This flexible structure enables users to add or

remove functionalities according to their specific needs, making OSeMOSYS suitable for different applications of varying complexities, scales, and objectives.

Currently, the OSeMOSYS code is available in two versions: the long code and the short code. The long code contains the complete set of equations and is more user-friendly and easier to understand. On the other hand, the short code was developed by merging equations from the long code to reduce computational time by eliminating the need to calculate and store intermediate values.

The objective function of OSeMOSYS is to minimize the cost, which is calculated as the sum of the discounted total cost for each region and year. Despite the difference in code length and complexity, both versions of OSeMOSYS produce the same key outputs.

“minimize cost: $\sum\{r \text{ in REGION, } y \text{ in YEAR}\} \text{ TotalDiscountedCost}[r,y]$ ”

2.4.5 Reference Energy System Mapping

When utilizing an optimization tool like OSeMOSYS to develop a model, it is necessary to create a mapping of the energy/electricity system to identify all the relevant technologies and fuels that will be involved in the analysis. This mapping is presented in the form of a schematic representation of the system, which is called a Reference Energy System (RES).

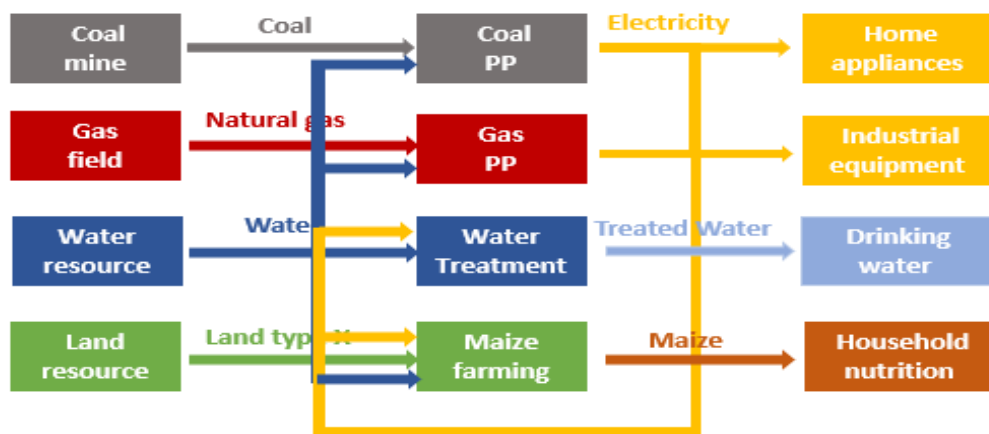


Figure 2.3: Simplified CLEWs concept

CHAPTER THREE: METHODOLOGY AND MODELLING STRUCTURE

A three-step approach has been developed for completing this study as depicted in figure 3.1. First, under the theoretical approach, literature review, desk study was done using various tools. After that, the data generation and analysis part are accomplished. This part was the most time-consuming of all. The data generation part was done using various software's which has been clearly illustrated in figure 3.1. Similarly, after that, the modeling has been done using online platform Momani and OSeMOSYS. The reference energy system that forms the heart of this modelling is shown in figure 3.1.

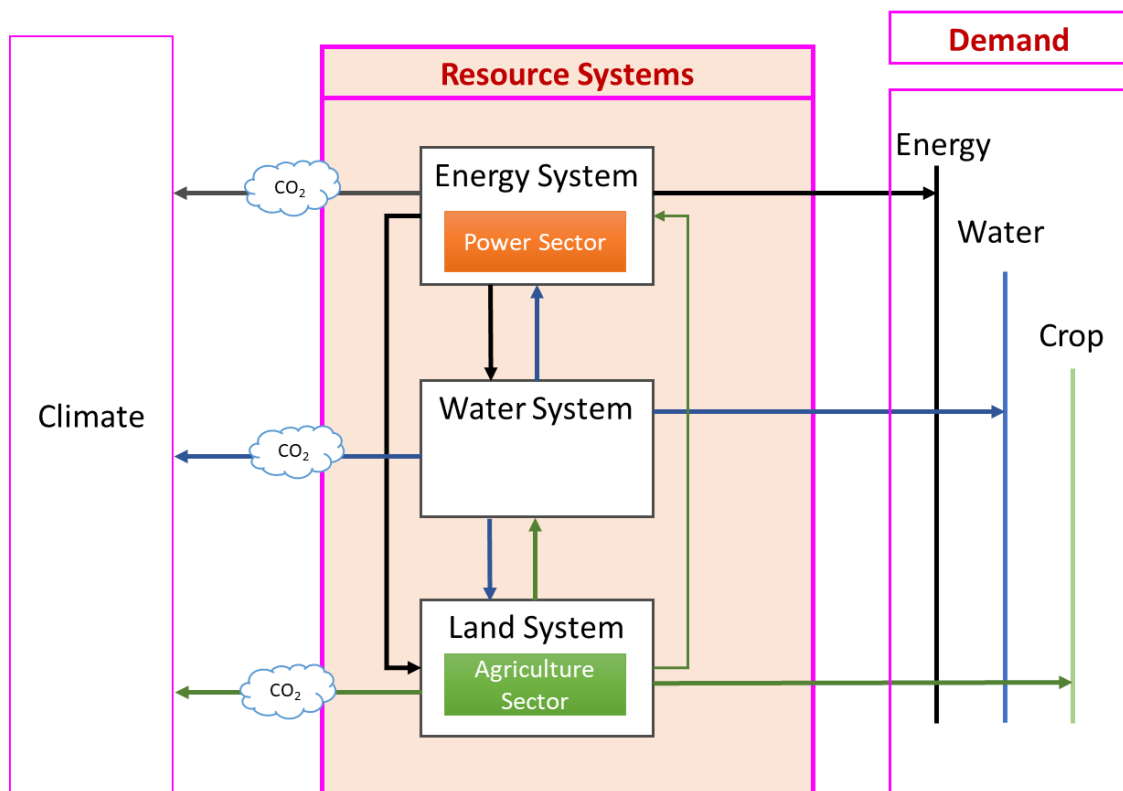


Figure 3.1: Reference Energy system for CLEWs

The detailed methodology diagram is shown in table 3.2. This methodology has been developed from our own rigorous learning and requirement.

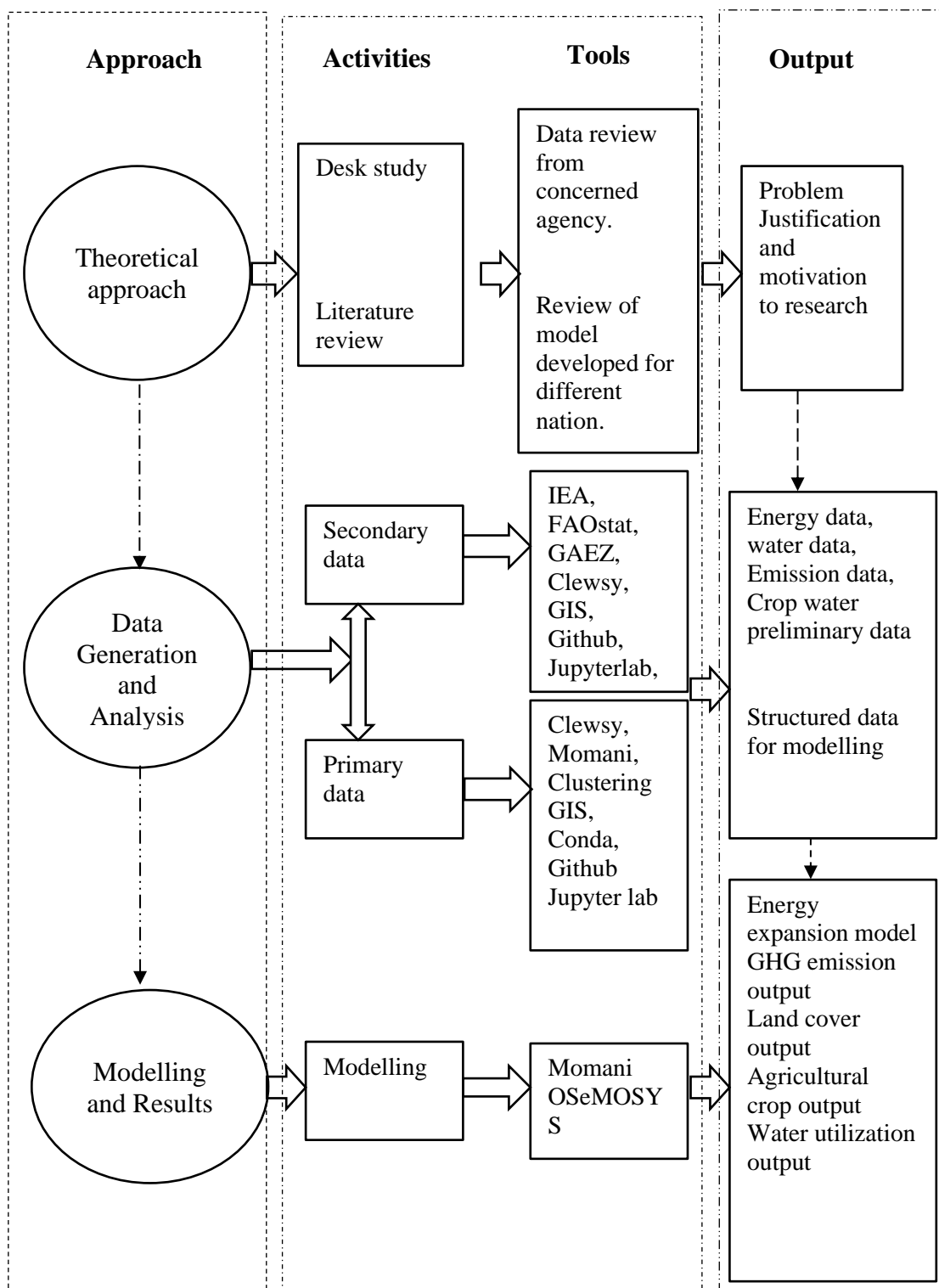


Figure 3.2: Research methodology and process figure

3.1 Nepal's model overview

Nepal is a country with population of 291,92,480 (According to the preliminary results

of the National Census-2078). An economic survey indicates that the usage of non-commercial forms dominates Nepal's overall energy consumption. Over the past ten years, energy consumption has grown at a 4% annual rate (MoF, 2021). With the increased utilization of modern energy resources, conventional energy consumption has decreased from 84% in 2010 to 67% in 2020. Commercial energy sources (coal, petroleum products, and electricity) are gradually taking over; their proportion will rise from 15% in 2010 to 31% in 2020, a 12% annual growth. Renewable energy sources are also developing steadily, with their contribution rising from 1% in 2010 to 2% in 2020. From 2% a decade ago, power consumption has recently grown to 4%.

Diesel is a key fuel source used in farm equipment and water pumps in the agriculture sector. Electricity has a relatively small role in the transport sector, where the main fuel sources are diesel, gasoline, and ATF. The nation's transportation industry uses 76% of the petroleum products that are imported. The roadmap for sustainable development goals places a strong emphasis on renewable energy and energy efficiency as Nepal develops toward this direction. The long-term strategy for Net-zero emissions by 2050 sets a goal of zero carbon emissions by that year, and the Second Nationally Determined Contributions (NDC) aims to reduce GHG emissions from both the energy and non-energy sectors. Nepal needs a paradigm shift away from dirty energy sources in order to achieve that.

To ensure that everyone has access to clean energy, the Ministry of Energy, Water Resources, and Irrigation (MOEWRI) intends to generate 10,000 MW by 2028 and provide 100% electricity access by 2023. By 2030, the 15th periodic plan of the National Planning Commission aims to generate about 4000MW from renewable energy sources (NPC, 2020). With a goal of producing more than 550MW by 2024, the government also wants to boost the proportion of solar energy generation through private sectors. Additionally, as part of the NDC target, Nepal intends to add 2100MW of solar energy to the national grid by 2030, meeting 15% of the nation's total energy consumption with renewable energy sources (Ministry of Finance, 2021).

As per the statical information of Nepalese agriculture (2018/19) the share of land cover analysis is shown below:

Table 3.1: Share of land Cover in Nepal

| Category | Area (1000 Hectares) | Share |
|--------------------------------|----------------------|--------|
| Agricultural Land Cultivated | 3,091 | 21.00% |
| Agricultural Land Uncultivated | 1,030 | 7.00% |
| Forest | 4,268 | 29.00% |
| Shrub land | 1,560 | 10.60% |
| Grass Land and Pasture | 1,766 | 12.00% |
| Water | 383 | 2.60% |
| Others | 2,620 | 17.80% |
| Total | 14,718 | 100% |

The table shows that the agriculture uncultivated land is limited, and this land should be capable of fulfilling the growing food demand of Nepal. The model has taken 7 types of land cover for analysis. the land cover and this areas in hectares used for 2018 A.D. is as shown below:

Table 3.2: Types of land cover and their percentage

| | |
|----------------------|-------------------|
| Barren land | 24.5 |
| Built-up land | 1.7 |
| Cropland | Model will assign |
| Forests | 42.68 |
| Grassland & Woodland | 33.26 |
| Water bodies | 3.83 |
| Other land | 7.16577 |

In terms of agriculture, the following data show the major food crops and cash crop of Nepal. The data has been taken from the Source: statistical data in Nepalese agriculture (2018/19)

Table 3.3: Crop production data of Nepal

| Cereal Crops | 2016/17 | | 2017/18 | | 2018/19 | |
|--------------|-----------|------------|-----------|------------|-----------|------------|
| | Area | Production | Area | Production | Area | Production |
| Paddy | 1,552,469 | 5,230,327 | 1,469,545 | 5,151,925 | 1,491,744 | 5,610,011 |
| Maize | 900,288 | 2,300,121 | 954,158 | 2,555,847 | 956,447 | 2,713,635 |
| Wheat | 735,850 | 1,879,191 | 706,843 | 1,949,001 | 703,992 | 2,005,665 |
| Millet | 263,596 | 306,704 | 263,497 | 313,987 | 263,261 | 314,225 |
| Buckwheat | 11,090 | 12,039 | 10,296 | 11,472 | 10,311 | 11,464 |
| Barley | 27,370 | 30,510 | 24,648 | 30,510 | 24,409 | 30,550 |
| Cash Crops | | | | | | |
| Oilseeds | 207,978 | 214,451 | 224,595 | 245,876 | 260,307 | 280,530 |
| Potato | 185,879 | 2,591,686 | 195,173 | 2,881,829 | 193,997 | 3,112,947 |
| Sugarcane | 70,807 | 3,219,560 | 78,609 | 3,679,508 | 71,625 | 3,557,934 |

The model has taken rice, maize, wheat, potato, and sugarcane as the crop for modeling. They have been taken based on the highest percentage of areas used for cultivation.

Based on the above data the model has segregated the cultivation of those 5 crops over rain feed and irrigation in the following pattern.

Table 3.4: The crop segregation based on rain feed and irrigated.

(Based on data for 2018 A.D.)

| Share per crop combination (ha) | Name of crop | Rain feed | | | Irrigated | | Total |
|---------------------------------|--------------|-----------|---------|---------|-----------|---------|----------|
| | | LR | IR | HR | II | HI | |
| RCP | Rice | 0 | 88,172 | 484,949 | 14,695 | 881,727 | 1,469,54 |
| MAI | Maize | 238,53 | 715,618 | 0 | 0 | 0 | 954,158 |
| WHE | Wheat | 0 | 35,342 | 247,395 | 424,105 | 0 | 706,843 |
| PTW | Potato | 39,053 | 0 | 0 | 117,16 | 39,053 | 195,268 |
| SGC | Sugarcane | 78,609 | 0 | 0 | 0 | 0 | 78,609 |

The water demand as per world meter info is taken as 9.86 billion m³ for the base year 2018 A.D and is predicted based on the GDP and historical trend.

The only emission factor used in the model is CO₂ emission because of the limitation on data availability.

3.2 Developing the Reference Energy System

The real energy system in the area or nation being studied is represented schematically by the Reference Energy System (RES). It depicts how energy moves horizontally from resources on the far left, through various technologies for energy transformation, to the final energy use on the far right.

The RES is the main skeleton of the model because based on this RES, the data are populated, and the demand driven optimization is done.

The Reference energy system for individual component is framed and then later all the individual components are re connected to find out their interlinkages(Almulla et al., 2017) (Gardumi et al., 2018).

3.2.1 RES for Energy System

The RES for energy system is formed through the interlinkages of technology and commodities of different fuels, their source, and their end use sector. There are altogether six fuels used in the model which are biomass, coal, diesel, gasoline, electricity, and LPG.

Also, the five-sector consuming these fuels are residential, industrial, commercial, transport and agricultural sectors. The interlinkages are done with appropriate input and output activity ratio to compensate the energy losses in transformation. The RES for energy system is given in annex.

3.2.2 RES for land and agriculture

The RES for land cover and agriculture is formed through the inter linkages of various landcover and crops used in the modelling. The model has included 7 land cover types which is shown in table 3.2 and altogether 5 crops are considered now for the modelling. These land cover and types of crops are termed into different technologies and commodities to interlink and form an appropriate RES which is shown in appendix 6.

3.2.3 RES for water systems

The water system represented here is two types that are surface water and pumped water. Water use is mainly represented for three sector which public supply, irrigation supply and power plant supply. The use of water system for its various use and the use of energy for water pumping and the use of water for agriculture are interlinked to for the RES for water system.

3.2.4 RES for land, Energy and Water system

The RES for overall land energy and water is formed through the linkage of individual RES based on their uses or nexus connection among one another. The overall nexus connection is given in appendix 3.

3.3 Developing the model

The final model has been developed through the interlinkages of all these reference energy systems. The clewsy platform is used to write up the code to interlink these RES. The code used for developing the model is shown in the appendix.

3.4 Primary Data collection

3.4.1 Energy System

The CLEWs optimization model Nepal is a multidisciplinary analysis tool, and during the calibration phase with the Nepal portfolio, it required a wide range of data from the energy, land (agricultural), water, and climate systems. Much of the data (for example, on the energy system) was gathered from NEA and other governmental sources as much as possible. However, one of the most difficult and time-consuming issues that climate

policy/energy modelers in Nepal are confronting is access to high quality and reliable data, whether on the energy or other sectors. So, we had to make logical assumptions to replace the erroneous or missing data in the model. This section examines the primary data, sources, and presumptions used in CLEWs optimization model Nepal.

The power system portfolio and the country need for other fuel types (from import and export sources) were the two categories of data inside the energy system. As of 20121, Nepal has roughly 1000 large and small hydropower project. Most of them are IPP and NEA projects, primarily very small to medium run-of-river stations. As there is not much reservoir hydro in Nepal majority of the projects were combined and represented in the model as a single, larger power generation element to streamline the model's structure.

All the hydro's have been combined to one large generator that has a considerable impact on the power system, hence they are each given a separate representation in the model power system. Based on the geography, capacity size, capacity factor, and generation method, the remaining hydro projects were examined.

Nepal does not possess Coal power plant and steam power plant, so their linkage is not considered in the model. The overall energy portfolio is listed in table 3.5.

Table 3.5: Main data used to calibrate the energy system in the model

| Data researched | | Data interpretation and presumption |
|---|--|--|
| Power System | | |
| Components (each power generation stations) | Capacity, location, nominal annual generation, actual annual generation, and operational life span | Capacity factor Efficiency Residual capacity |
| Cost | Capital cost, fixed cost, and variable costs. Information on the generic cost of technology. | As there was a lack of information, generic cost data was assigned for each technology. |
| Demand | The electricity demand is collected from NEA annual report 2018. The sectoral energy demand | The availability factors were not provided. Annual demand was specified for each time slice, along with a specified demand portfolio |

| | | |
|--|---|---|
| | is collected from IEA reports. The demand is forecasted to 2050 using econometric models. | and power demand for each sector (residential, commercial, industry, transportation). Time slices were divided into daily intervals and split by season |
| Other information | Transmission loss (10%) | Reference data was allocated |
| Rest of the energy system | | |
| Non-electrical fuels | Accumulated annual end-use fuel demand was considered, along with domestic fuel production and import/export fuel supplies. | The demand for non-electrical fuels that can be stored was projected annually, rather than for each time slice. |
| Cost | Fuel cost and annual forecast to 2050 | Assumption has been made to project the fuel cost to 2050 |
| Data on the energy linkages between land and water systems | Energy demand in agriculture, such as diesel used to run agricultural machinery, and in water systems, including energy used for water pumping and water treatment facilities, were considered. | |

Temporal representation and specific demand portfolio for the power system

The model allows for user-defined temporal representation that can be altered in response to a query. This is crucial for renewable energy sources that are changeable, like solar and wind, whose output varies greatly depending on the season and the location of the facility.

The model splitted the year into two season and each season is splitted into three splits based on the time of hours of operation namely base, intermediate, and peak. So, overall, 6 splits in a year were formed whose information's shown below:

Table 3.6: Temporal representation of power system in the model

| Season/month | English month | Nepali month | No. of hours of operation | | |
|---------------|---------------|-----------------|---------------------------|-----|------|
| | | | Base | Int | Peak |
| S1 (6 months) | May-Oct | Jestha-Kartik | 8 | 12 | 4 |
| S2 (6 months) | Nov-Apr | Mangsir-Baisakh | 8 | 12 | 4 |

Based on the hourly electrical load of Nepal in 2018, the specified portfolio characteristic of the Nepal's power demand was defined for each of the time slices, as shown in Table 3.7. This parameter is important, as it specifies the annual fraction of power demand that is required in each defined time slice. The reference has been taken from NEA load curve and energy balance diagram whose detail has been given in annex.

Table 3.7: Specified demand portfolio character.

| Season/month | Month | | Specified annual demand (%) | | |
|---------------|---------|-----------------|-----------------------------|------|------|
| | | | Base | Int | Peak |
| S1 (6 months) | May-Oct | Jestha-Kartik | 0.16 | 0.25 | 0.08 |
| S2 (6 months) | Nov-Apr | Mangsir-Baisakh | 0.16 | 0.25 | 0.08 |

3.4.2 Land system

The land-use portfolio of Nepal was shaped using two main categories of data: availability and allocation of land, and land-use portfolio to meet food and energy demands. The main data collected for the land portfolio in this model are summarized in Table 3.8.

Table 3.8: Main data used to calibrate the land system in the model

| Collected data | | Data analysis and assumptions |
|------------------------------|---|---|
| Type of land available Nepal | <ul style="list-style-type: none"> Land available in Nepal by type: agriculture, forests, barren, water body, and built-up lands, along with their respective sizes. | <ul style="list-style-type: none"> Data collected from Nepalese statistics of agriculture report |
| Agriculture | <ul style="list-style-type: none"> Type of crops in Nepal per hectares | <ul style="list-style-type: none"> Project the future growth in land use for built-up and |

| | | |
|--|---|--|
| | <ul style="list-style-type: none"> • Annual demand for main crops growth in Nepal • Clustered data for crop yield (t/ha) • crop-specific agro-climatic assessment • soil/terrain limitations • Water use (rained fed vs irrigated) • Agricultural intensity (low, intermediate, high input level) | <p>agricultural lands based on population growth and historical trends.</p> <ul style="list-style-type: none"> • Choose five crops that occupy more than 90% of agricultural lands for the purpose of clustering and analyzing future growth. • Majority of the data will be collected using the GAEZ model (Global Agro-Ecological Zoning). |
|--|---|--|

In order to determine crop suitability for different land systems, a land clustering methodology was utilized. To simplify the modeling process and analyze extensive area data, general and crop-specific agro-climatic indicators, along with soil/terrain limitations and water availability constraints, were combined into a single set. The Global Agro-Ecological Zoning (GAEZ) model was employed to collect information on crop suitability estimation for different types of land. The K-means approach is used by GAEZ to group together lands (cells) with comparable achievable yield potential data. With the use of an elbow error graph that GAEZ has produced for the research area, the user of the GAEZ model can verify the optimal number of clusters they have selected that reflects the outcome of clustering done with the GAEZ model.

Geospatial clustering of crops, precipitation, and agricultural data

The clustering is done using the code developed by Alexander Korkovoles under supervision of Abhisek Srinivas and Thomas Alfstad. The version of code can be downloaded from github. After downloading and extracting the file, there is a procedure that is developed to do the clustering.

The following procedure can generate Geospatial clustering data for CLEWs for any area of our subject study based on the code which is downloaded from github. The procedure developed in this model is attached in the appendix.

3.4.3 Water and climate systems

The current version of the model only tracks water and climate data. This means that only

one-way interaction is possible for water availability in Nepal and changes in demand for water in different sectors. Climate data, on the other hand, includes tracking CO₂ emissions for each activity within and between systems. Forestry is a crucial activity within the model as it can aid in climate change mitigation by absorbing CO₂ from the atmosphere. By assigning a negative value of variable cost to forest lands, the model considers reforestation as part of its optimization analysis. However, due to uncertainties surrounding the role of Nepal's forests in absorbing CO₂ from the atmosphere versus the amount they emit, this option has not been activated in the current scenarios. The matter is being investigated for future scenarios.

3.5 Data Input to model

3.5.1 Set data input

a. Commodity

There are altogether 82 commodities in the model whose list is attached in annex 1.

b. Technology

The technology set data input list for the model has been given in annex 2.

c. Year split

The modelling has been done for the period ranging from 2018 to 2050 A.D.

d. Time slice

Table 3.9: Time slice used in the model.

| Slices | Description |
|---------|-----------------------|
| SEA1BAS | Season 1 Base |
| SEA1INT | Season 1 Intermediate |
| SEA1PEK | Season 1 peak |
| SEA2BAS | Season 2 Base |
| SEA2INT | Season 2 Intermediate |
| SEA2PEK | Season 2 peak |

e. Emission

Only CO₂ emission is considered in this modelling.

f. Mode of Operation

Altogether there are 31 modes of operation in this model which is listed below:

Table 3.10: Mode of operation

| Mode | Category | Description |
|------|------------------------------------|------------------------------------|
| 1 | MAIHI | Maize High Irrigated |
| 2 | MAIII | Maize Intermediate Irrigated |
| 3 | MAIHR | Maize High Rain feed |
| 4 | MAIIR | Maize Intermediate Rain feed |
| 5 | MAILR | Maize Low Rain feed |
| 6 | PTWHI | Potato High Irrigated |
| 7 | PTWII | Potato Intermediate Irrigated |
| 8 | PTWHR | Potato High Rain feed |
| 9 | PTWIR | Potato Intermediate Rain feed |
| 10 | PTWLR | Potato Low Rain feed |
| 11 | RCPHI | Rice High Irrigated |
| 12 | RCPII | Rice Intermediate Irrigated |
| 13 | RCPHR | Rice High Rain feed |
| 14 | RCPIR | Rice Intermediate Rain feed |
| 15 | RCPLR | Rice Low Rain feed |
| 16 | SGCHI | Sugarcane High Irrigated |
| 17 | SGCII | Sugarcane Intermediate Irrigated |
| 18 | SGCHR | Sugarcane High Rain feed |
| 19 | SGCIR | Sugarcane Intermediate Rain feed |
| 20 | SGCLR | Sugarcane Low Rain feed |
| 21 | WHEHI | Wheat High Irrigated |
| 22 | WHEII | Wheat Intermediate Irrigated |
| 23 | WHEHR | Wheat High Rain feed |
| 24 | WHEIR | Wheat Intermediate Rain feed |
| 25 | WHELRL | Wheat Low Rain feed |
| 26 | Barren and sparsely vegetated land | Barren and sparsely vegetated land |
| 27 | Built-up land | Built-up land |

| | | |
|----|----------------------|------------------------------------|
| 28 | Forest land | Forest land |
| 29 | Grassland & woodland | Barren and sparsely vegetated land |
| 30 | Other land | Built-up land |
| 31 | Water bodies | Forest land |

3.5.2 Demand Data

There are two demands addressed in this model. They are accumulated annual demand and specified annual demand.

a. Accumulated annual Demand.

The accumulated demand collection for all sectors of energy, water, crops was done through various means which is already described in the above section. The accumulated demand is forecasted to 2050 taking the reference of 2018 A.D.

The data for the accumulated demand is shown in annex 3.

b. Specified annual demand.

The specified annual demand is only included for sectoral energy demand of electricity. The electricity used in each sector (Industrial, commercial, transport, residential, agricultural) is taken and is forecasted up to 2050 A.D and is used as the data in the model.

3.5.3 Input and Output Activity Ratio:

Input activity ratio links the commodity with its corresponding technology. Different activity ratios are used to link different commodities to different technology based upon their rate of usage. Output ratio is the rate of output of the fuel at which the technology is operating. This ratio is also different for different modes of operation and different output.

3.5.4 Parameters

The data used for different parameters used in the model are explained below:

Capacity factor

The model inputs the capacity factor for solar only which is 0 for season one base period, season1 peak period and season two base period and season 2 peak period whereas it is

0.3 for season 1 intermediate period and season 2 intermediate period.

Availability factor

The availability factor data for hydro is taken as 60 % and for wind, it is taken as 25%.

Emission factors

The data for emission factor is taken from a model built for Malaysia. The reference of which is given below.

Table 3.11: Emission factor used in the model

| Fuel | Ton CO ₂ eq/PJ | Million tones CO ₂ /PJ |
|-----------|---------------------------|-----------------------------------|
| DEMAGRDSL | 69788.11 | 0.0698 |
| DEMAGRGS | 66795.07 | 0.0668 |
| DEMAGRHFO | 71249.73 | 0.0712 |
| DEMCOMDSL | 69788.11 | 0.0698 |
| DEMCOMHFO | 71249.73 | 0.0712 |
| DEMCOMLPG | 58729.29 | 0.0587 |
| DEMCOMNGS | 50342.21 | 0.0503 |
| DEMINDCOA | 92810.28 | 0.0928 |
| DEMINDDSL | 69788.11 | 0.0698 |
| DEMINDGS | 66795.07 | 0.0668 |
| DEMINDHFO | 71249.73 | 0.0712 |
| DEMINDKER | 71515.11 | 0.0715 |
| DEMINDLPG | 58729.29 | 0.0587 |
| DEMINDNGS | 50342.21 | 0.0503 |
| DEMOTHLPG | 58729.29 | 0.0587 |
| DEMOTHNGS | 50342.21 | 0.0503 |
| DEMPWRCOA | 92810.28 | 0.0928 |
| DEMPWRDSL | 69788.11 | 0.0698 |
| DEMPWRNGS | 50342.21 | 0.0503 |
| DEMRESKER | 71515.11 | 0.0715 |
| DEMRESLPG | 58729.29 | 0.0587 |
| DEMRESNGS | 50342.21 | 0.0503 |
| DEMTRADSL | 69788.11 | 0.0698 |

| Fuel | Ton CO ₂ eq/PJ | Million tones CO ₂ /PJ |
|-----------|---------------------------|-----------------------------------|
| DEMTRAGSL | 66795.07 | 0.0668 |
| DEMTRAHFO | 71249.73 | 0.0712 |
| DEMTRANGS | 50342.21 | 0.0503 |
| DEMTRAOHC | 71249.73 | 0.0712 |

Capital Cost

The capital cost associated with hydro and solar is shown in table 3.12.

Table 3.12: Capital cost of technology used in model.

| Technology | Cost | Unit | Technology | Cost | Unit |
|-------------|------|-------------|-------------|------|-------------|
| LNDMAIHINPL | 70 | \$/hectares | LNDSGCHINPL | 70 | \$/hectares |
| LNDMAIHRNPL | 40 | \$/hectares | LNDSGCHRNPL | 40 | \$/hectares |
| LNDMAIINPL | 60 | \$/hectares | LNDSGCIINPL | 60 | \$/hectares |
| LNDMAIIRNPL | 28 | \$/hectares | LNDSGCIRNPL | 28 | \$/hectares |
| LNDMAILRNPL | 22 | \$/hectares | LNDSGCLRNP | 22 | \$/hectares |
| LNDOTHNPL | | \$/hectares | LNDWATNPL | | \$/hectares |
| LNDPTWHINPL | 70 | \$/hectares | LNDWHEHINPL | 70 | \$/hectares |
| LNDPTWHRNPL | 40 | \$/hectares | LNDWHEHRNPL | 40 | \$/hectares |
| LNDPTWIINPL | 60 | \$/hectares | LNDWHEIINPL | 60 | \$/hectares |
| LNDPTWIRNPL | 28 | \$/hectares | LNDWHEIRNPL | 28 | \$/hectares |
| LNDPTWLRNPL | 22 | \$/hectares | LNDWHELRNPL | 22 | \$/hectares |
| LNDRCPHINPL | 70 | \$/hectares | PWRHYDN01 | 3500 | \$/kW |
| LNDRCPHRNPL | 40 | \$/hectares | PWRSOLN01 | 1000 | \$/kW |
| LNDRCPIINPL | 60 | \$/hectares | PWRTRN001 | 2800 | \$/kW |
| LNDRCPIRNPL | 28 | \$/hectares | PWRWND001 | 1500 | \$/kW |
| LNDRCPLRNPL | 22 | \$/hectares | | | |

Fixed cost

The fixed cost for hydro, wind and solar is taken as 60, 40 and 30 in the modelling. The unit is \$/kW/year.

Variable cost

For hydro solar and wind, the variable cost is taken as 1,0.5 and 0.5 respectively whereas the cost involved in the transmission is also taken as 1. The unit for variable cost is \$/GJ.

Similarly, the fuel cost is referenced from the data of Sri Lanka which is shown in appendix.

3.5.5 Constraints

There are three constraints used in models. They are activity constraints, capacity constraints and investment constraints. The model has been optimized by limiting these constraints.

Table 3.13: Constraints used in the model

| Capacity Constraints | Descriptions |
|---|---|
| Capacity Of One Technology Unit | If the user sets the capacity of one new unit of technology, the technology will only be installed in multiples of that capacity, and the problem will become a Mixed Integer Linear Problem. |
| Total Annual Max Capacity | The maximum total capacity permitted for a technology in a particular year, including both residual and previously installed capacity. |
| Total Annual Min Capacity | The minimum total capacity allowed for a technology in a specified year, taking into account both residual and previously installed capacity. |
| Investment Constraints | |
| Total Annual Max Capacity Investment | The maximum power capacity that a technology can have, typically expressed in power units. |
| Total Annual Min Capacity Investment | The minimum power capacity that a technology must have, typically expressed in power units. |
| Activity Constraints | |
| Total Technology Annual Activity Upper Limit | The maximum total level of activity permitted for a technology in a single year. |
| Total Technology Annual Lower Limit | The minimum total level of activity permitted for a technology in a single year. |
| Total Technology Mode Period Activity Upper Limit | The maximum total level of activity permitted for a technology over the entire duration of its operation over a modeling period. |

| | |
|--|---|
| Total Technology Model Period Activity Lower Limit | The minimum total level of activity permitted for a technology over the entire duration of its operation as modelled in the analysis. |
|--|---|

3.5.6 Model Run

The Yaml file that consists of the code of the model is first loaded into the local host:8080 which opens the model management infrastructure. This file will consist of almost all the linkage and relation that will build the reference energy system for the model.

Using OSeMOSYS to run

After this, the input has been given in the model. The inputs that we put have already been described in the above section. After the model is ready, the scenario is downloaded as ZIP file which is then extracted. This file consisted of the model and data file of the model scenario developed.

The model runs on a virtual platform OSeMOSYS. The model is then uploaded in the OSeMOSYS system and then it is run to get the corresponding output. The visualization of the result and others are described in the discussion section of this project.

CHAPTER FOUR: RESULTS AND DISCUSSION

Two scenario directions are investigated for 2018 to 2050 timeline. The purpose of developing scenarios was to analyze the potential synergies and trade-offs between Nepal's NDC policies and actions, and their effects on energy, land, climate, and water resources. Additionally, the scenarios aimed to determine if these policies would bring Nepal closer to its CO₂ emission reduction targets. The analysis began by exploring a business-as-usual scenario, followed by modeling the policies aligned with the NDC target for 2030. The results obtained from the model are represented in graphical form below.

4.1 BAU scenario

The business-as-usual scenario in energy modeling typically includes assumptions about future population growth, economic development, and technological progress. These assumptions are used to project the demand for energy across various sectors, such as transportation, residential, commercial, and industrial, as well as the supply of energy from different sources, such as fossil fuels, nuclear, and renewables.

BAU scenario is the main model which is formed tracking the population growth rate of 2018 AD, gross domestic growth rate of 2018 AD, industrial value addition of 2018 AD, commercial value addition of 2018 AD. Similarly, this scenario replicates the energy, land and water demand growth rate based on the historical data collected till 2018 AD.

Overall, developing a business-as-usual scenario in energy modeling is an essential step in understanding the current and future energy landscape, identifying potential challenges and opportunities, and formulating effective policies and strategies to address them.

4.1.1 Gross final energy consumption by sector

Figure 4.1 illustrates the projected gross final energy consumption for various sectors from 2018 to 2050. The graph shows that the total energy consumption will increase from 582 PJ in 2018 to 1670 PJ by 2050 under a business-as-usual scenario. The residential sector is expected to have the highest final energy consumption, while the transport sector is projected to experience the fastest growth in energy consumption compared to other sectors.

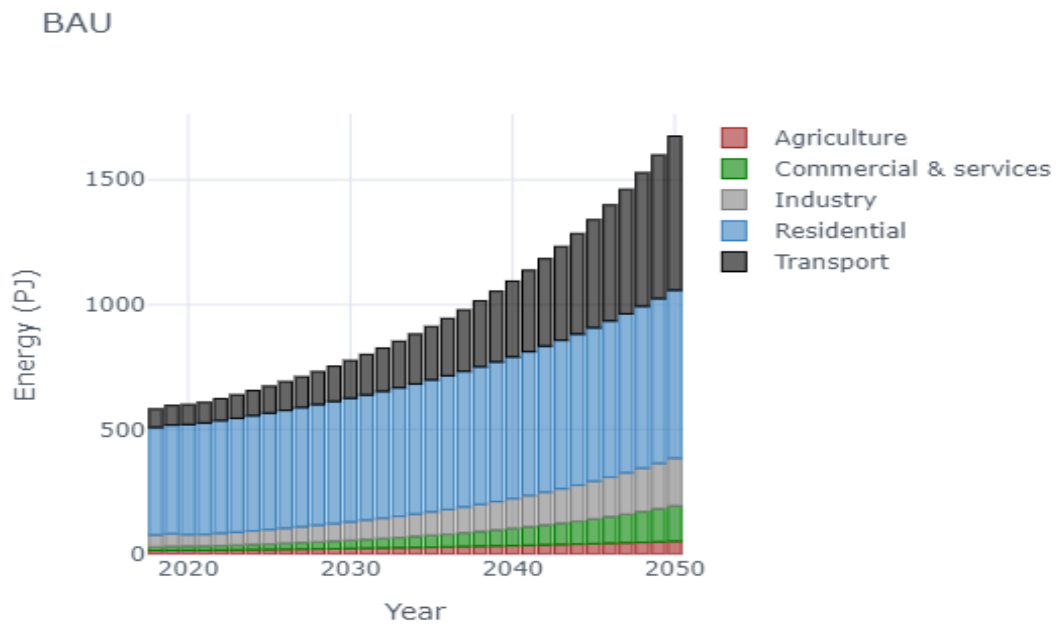


Figure 4.1: sectoral energy consumption

4.1.2 Gross final energy consumption by fuel

The graph displaying the gross final energy consumption by fuel indicates that without policy interventions, the country's reliance on fossil fuels will remain high. Under a business-as-usual scenario, diesel energy consumption is projected to increase from 77.3 PJ in 2018 to 638 PJ by 2050. Similarly, electricity consumption is expected to rise from 23.6 PJ to 154 PJ during this period.

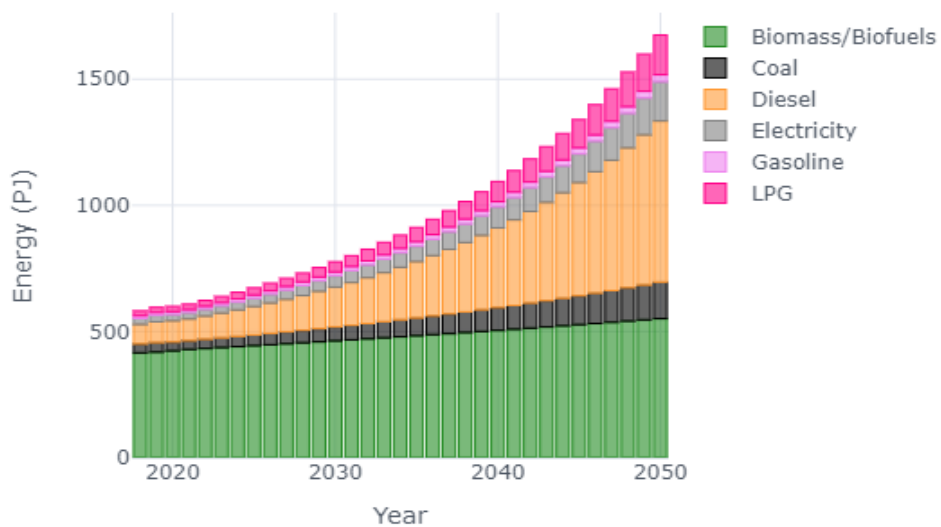


Figure 4.2: Gross final energy consumption by fuel

4.1.3 Power generation capacity details

The details of power generation capacity in the modelling period based on the least-cost technology mix that can meet the electrical demand are shown in figure 4.3. The graph indicates that hydropower will be the most dominant source of energy, with a capacity of up to 9.7 GW by 2050. Solar and wind energy sources have a relatively low percentage in the mix, as their availability and capacity factors, as well as their lifetimes, are lower compared to hydropower.

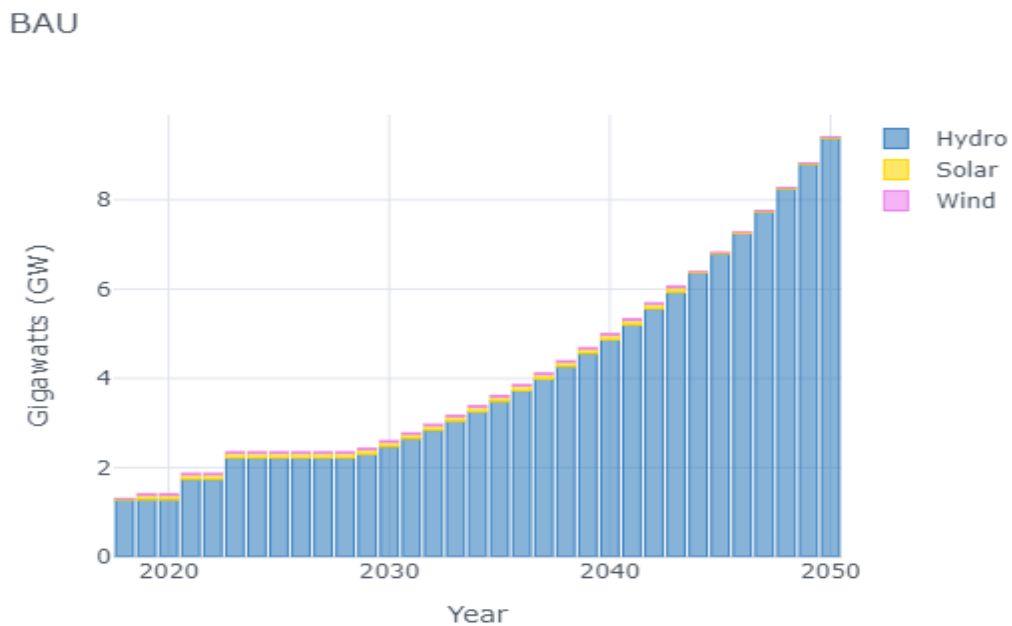


Figure 4.3: Power Generation capacity

4.1.4 Domestic energy production

The least cost domestic energy production over the modelling period has been illustrated in figure 4.4. The graph indicates a significant increase in the production of hydro energy from 22 PJ in 2018 to 184 PJ in 2050. Biomass is expected to be the highest produced domestic energy source in the modelling period, with a share that is projected to rise to 551 PJ. This highlights the potential for the country to rely more on renewable domestic energy sources to meet its energy needs, thereby reducing its dependence on imported energy.

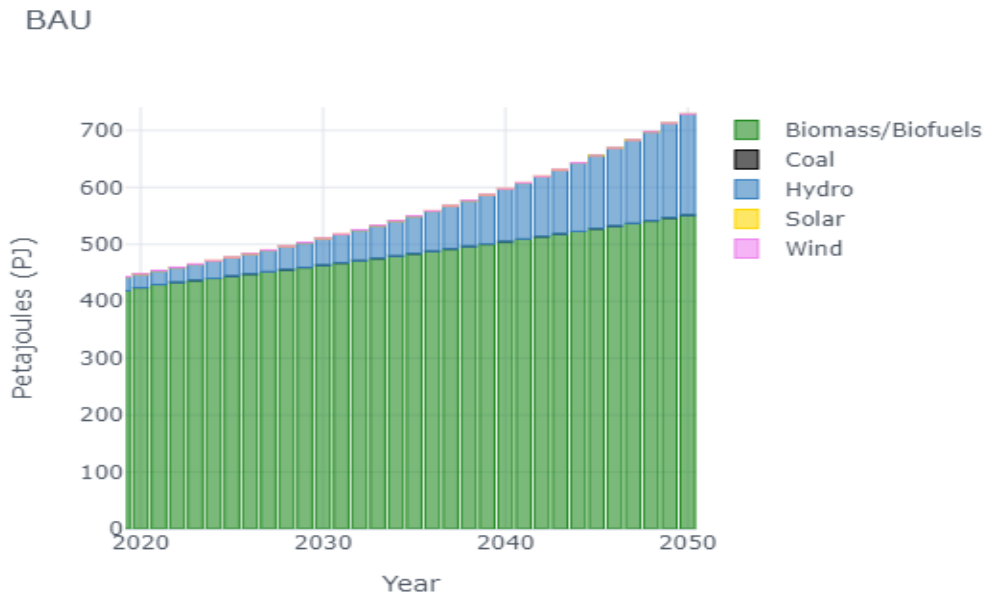


Figure 4.4: Domestic energy production

4.1.5 Energy imports

The projection of energy imports graph indicates that the country will continue to have a high dependence on energy imports, with diesel imports projected to rise from 77.3 PJ in 2018 to 638 PJ by the end of the modelling period. However, the country is expected to achieve energy independence for electricity by 2023. The graph also highlights a considerable increase in the imports of petrol and coal for the transport and industrial sectors, respectively, as well as a rise in LPG imports for the industrial sector.

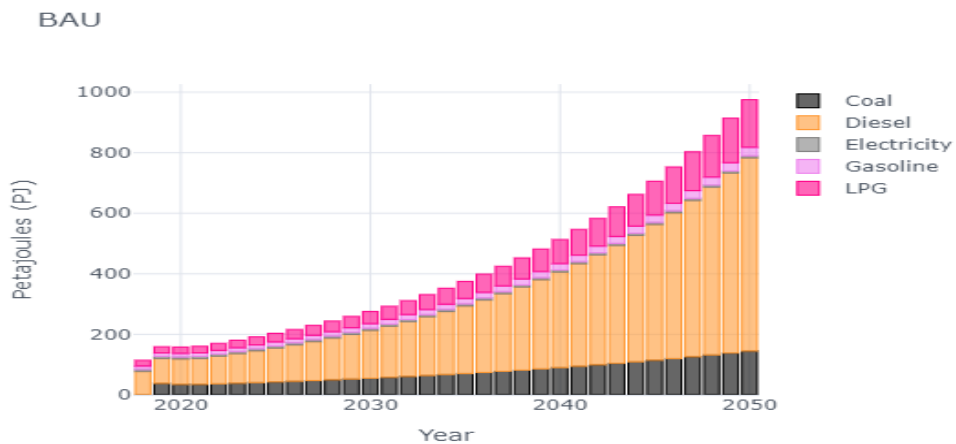


Figure 4.5: Energy Imports

4.1.6 Area by crop

Figure 4.6 provides an overview of the area of crops required to meet the current food demand over the modelling period. The graph highlights that rice is the crop with the highest area of cultivation, occupying 15,150 sq.km of land in 2018, and projected to increase to 25.5 sq.km by 2050. The total cultivated area is expected to increase from 33,500 sq.km to 54,500 sq.km to meet the growing food demand. This indicates the need for efficient and sustainable farming practices to ensure food security while minimizing the impact on the environment.

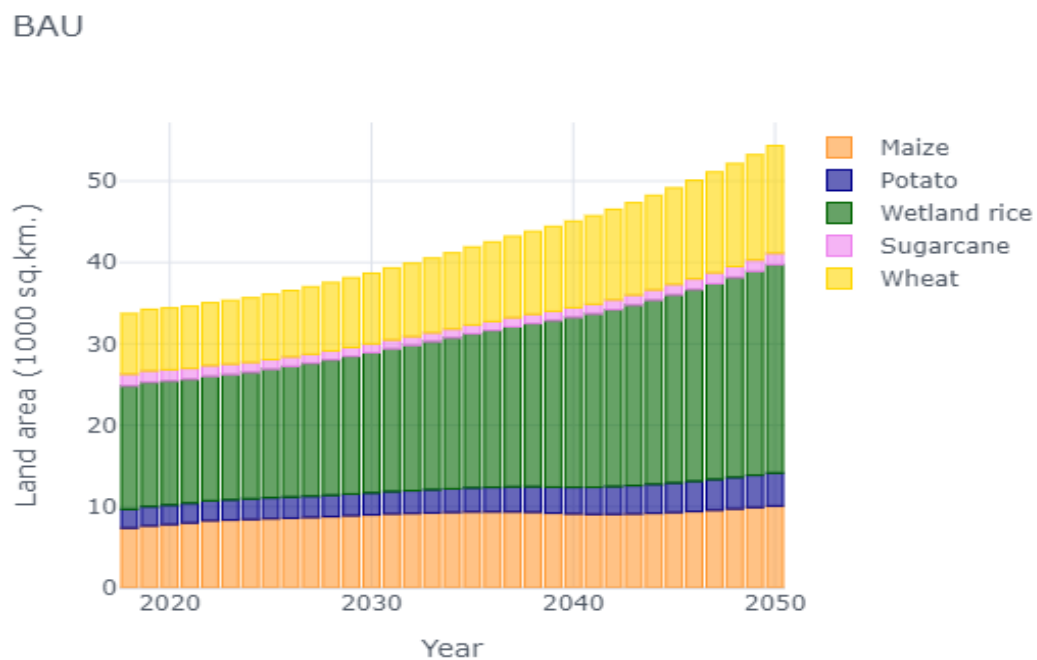


Figure 4.6: Area by crop

4.1.7 Area by land cover type

The acquisition of land cover over the modelling period to meet the food and water demand is projected through figure 4.7. The forest has been constrained to maintain over 40 percent of total land. The barren land and grassland are being used to convert to agricultural land to meet the crop demand. The barren land decreases from 24500 sq.km to 10000 sq.km in the modelling period whereas the agricultural land increases from 33000 sq. km to 54330 sq.km. There is also a rise in built up land for settlement over the modelling period.

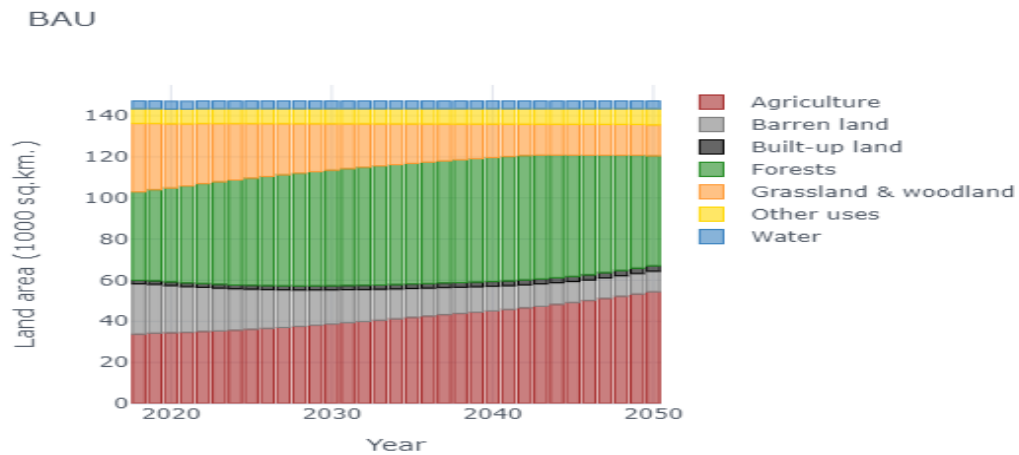


Figure 4.7: Area by land cover type

4.1.8 Crop production

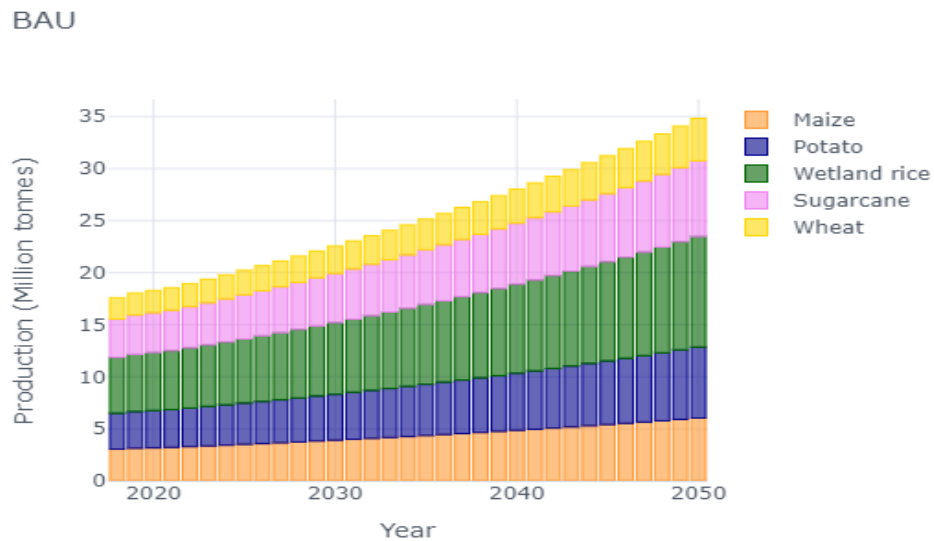


Figure 4.8: crop production

Figure 4.8 depicts the crop production in millions of tons. It shows that the production of these five crops will almost double over the modelling period.

4.1.9 Yield

The model depicts that the productivity increase in terms of yield over the modelling period. As the farming is going over low rain feed high rain feed and medium irrigation to high irrigation, there is rise in productivity. The yield of sugarcane is almost double as per the model. Similarly, there is also a significant increase in yield of other crops too.

Increase in yield implies less consumption of land to produce the same tones of products.

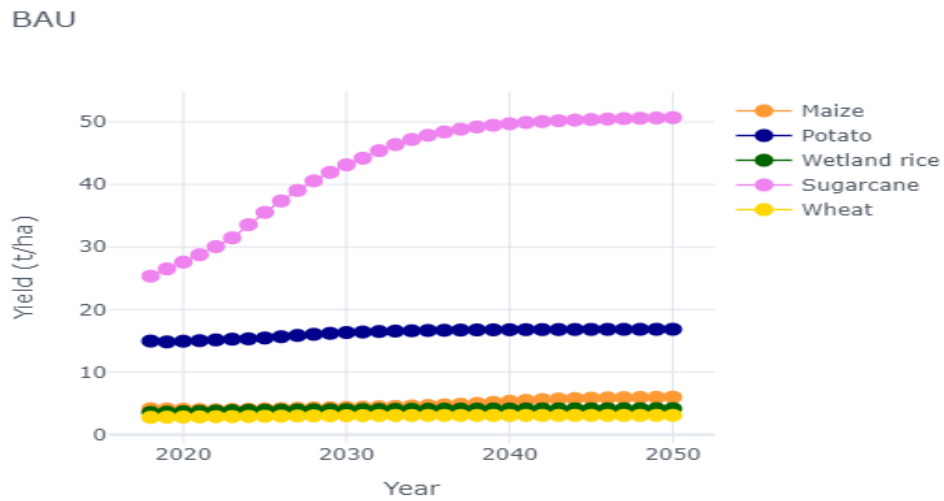


Figure 4.9: Yield

4.1.10 Water demand

The optimization of water demand of the modelling period is illustrated in figure 4.10. Majority of water demand in Nepal is for public which is 9.8 billion cubic meter in 2018 A.D and rises to 10.9 billion cubic meter in 2018 A.D. the water requirement in agricultural sector through irrigation doubles by 2050 A.D. and the water requirement in power sector goes 8-fold over the period i.e., from 0.11 billion cubic meter to 0.922 billion cubic meter.

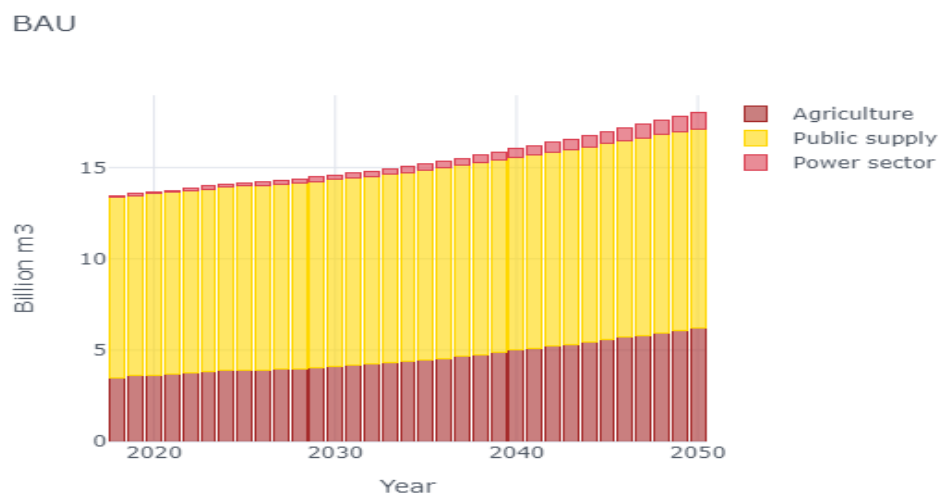


Figure 4.10: Water demand

4.1.11 Water balance

There is rainfall of 191 billion cubic meters annually and the irrigation demand is increasing as already depicted in the previous figure. All these waters is balanced through surface water run-off and evapotranspiration as shown in the figure itself.

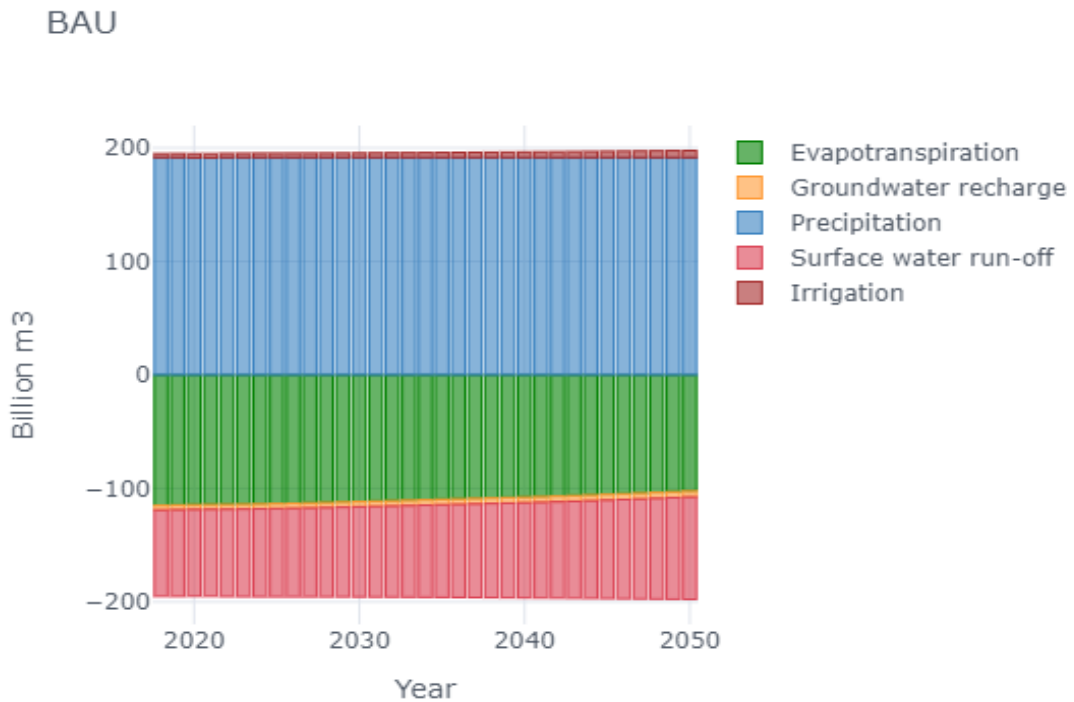


Figure 4.11: Water Balance

4.1.12 CO₂ emissions by sector

Figure 4.12 shows the sectoral CO₂ emission by source. The emission rises from 49 million tons in 2018 to 119 million tons by 2050 if no any intervention is made. The transport sector will be the major contributor with almost 42 million tons of Co₂ equivalent emission by 2050. Similarly, industries will be raising their emissions from 3.57 million tons to 14.2 million tons of CO₂ equivalent by 2050.

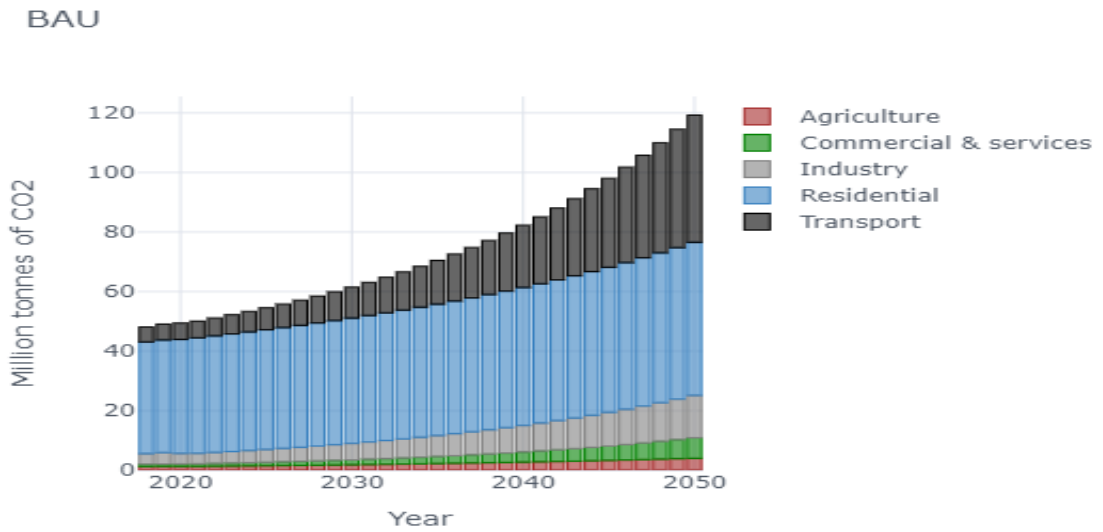


Figure 4.12: CO₂ emission by sector

4.1.13 CO₂ emission by Source

Based on the nexus connection of the land energy and water system, the corresponding impact made by them is depicted in figure 4.13. The biomass/ biofuels sector is the leading CO₂ emission source. The individual CO₂ emission contribution of each fuel source in a business-as-usual scenario is rapidly increasing. The emission rises from 49 million tons in 2018 to 119 million tons by 2050 if no intervention is made. At the current rate of diesel vehicles, the emission from diesel will only be 9 folds over the modelling period.

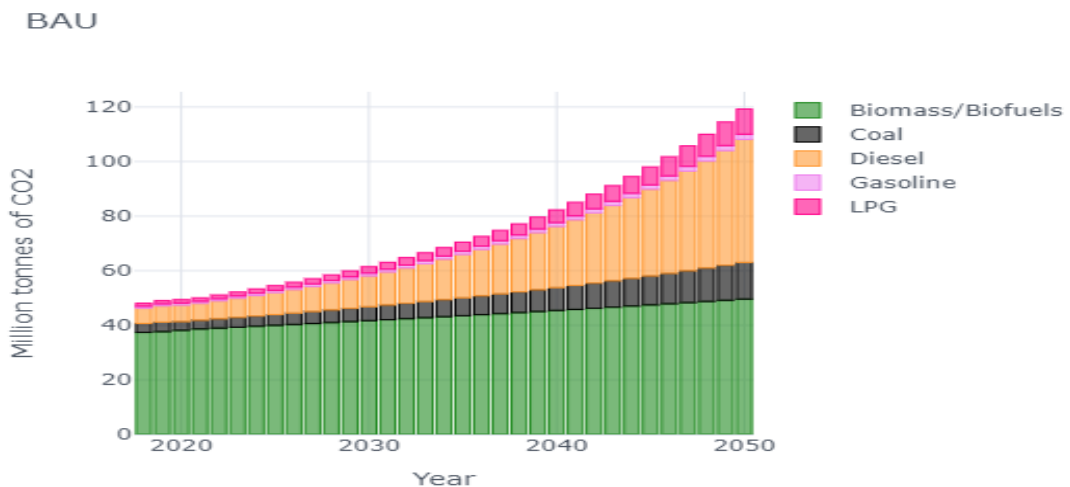


Figure 4.13: CO₂ emission by source

4.1.14 Area by crop (irrigated)

Figure 4.14 depicts the irrigated area requirement for various crops over the modelling period. There is a rise in the irrigated area for rice and sugarcane from 9000 sq.km. and 667 sq.km. to 22000 sq.km and 1434 sq.km respectively over the modelling period. Similarly, potato and wheat are showing more requirement towards high rain feed system.

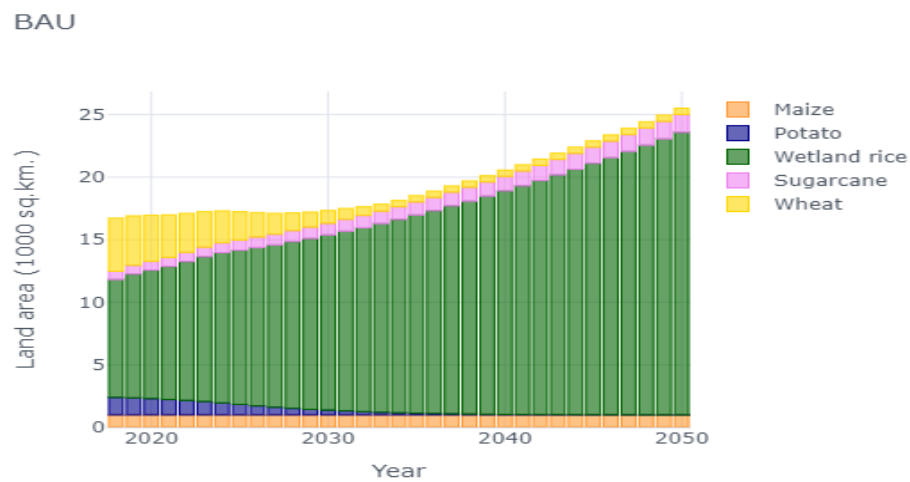


Figure 4.14: Area by crop(irrigated)

4.1.15 Area by crop (Rain feed)

Potatoes and wheat are showing increased rain feed land usage for meeting up the optimized scenario. Figure 4.15 depicts the same data as figure 4.14 but in terms of rain feed.

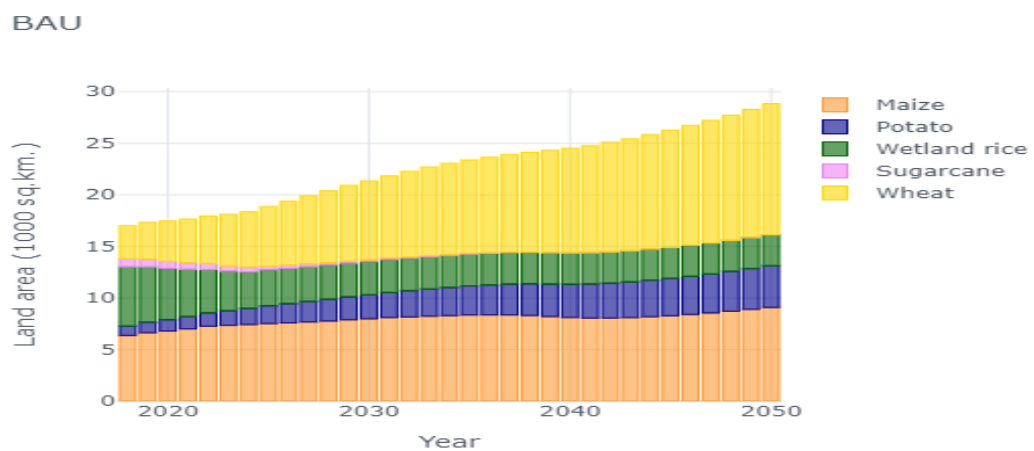


Figure 4.15: Area by crop (rain feed)

4.2 Scenario and comparison with BAU

This model also consists of a scenario named scenario 1 which has replicated some of the NDC target of Nepal. The scenario has been formed over the following baseline:

- Cooking shall be replaced by 25% electric by 2030 A.D
- There will be 40% share of electric vehicle on all kinds of vehicle import by 2030 A.D
- The share of forest will be 45% of total land cover by 2030 A.D

The PJ demand of electricity to replace biofuels demand can be calculated as:

$$\text{Electricity_additional requirement} = \text{Biofuel demand}_{2030} \times \text{efficiency chain} \times \text{Scenario adoption efficiency}$$

Similarly, the PJ demand for electricity to replace fossil fuel in transport sector is calculated as:

$$\text{Electricity_additional requirement} = \text{fossilfuel demand}_{2030} \times \text{efficiency chain} \times \text{Scenario adoption efficiency}$$

4.2.1 Comparison of gross final energy consumption by sector

Under scenario 1, the gross final energy consumption reduces by 135 PJ by 2030. As the biomass in residential cooking is being replaced with electric energy, the equivalent energy requirement has drastically reduced. The same is going on with transportation as fossil fuel car are replaced by electric ones.

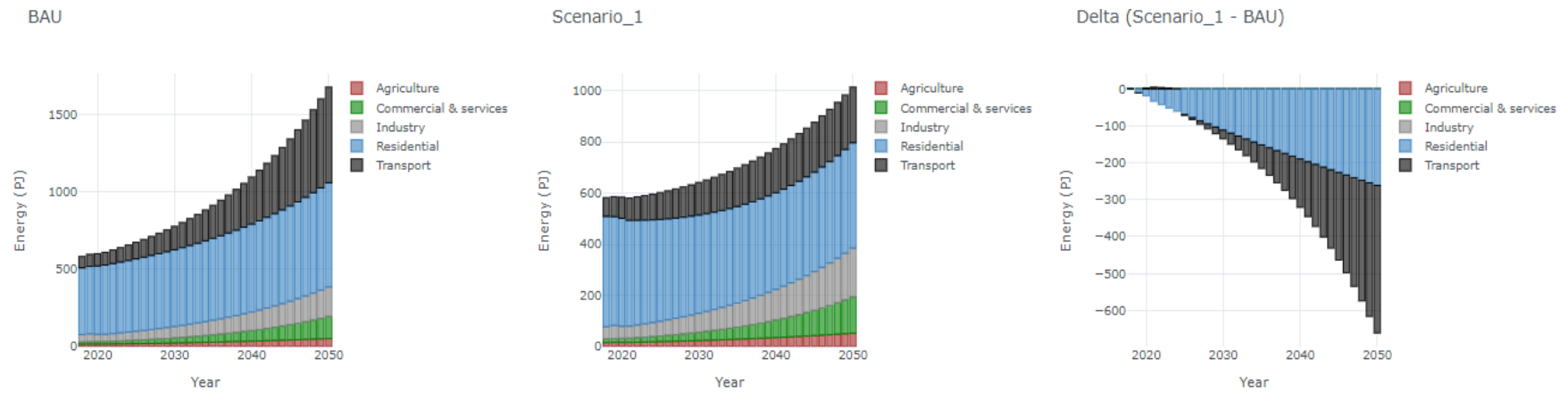


Figure 4.16: Comparison of gross final energy consumption by sector

4.2.2 Comparison of gross final energy consumption by fuel

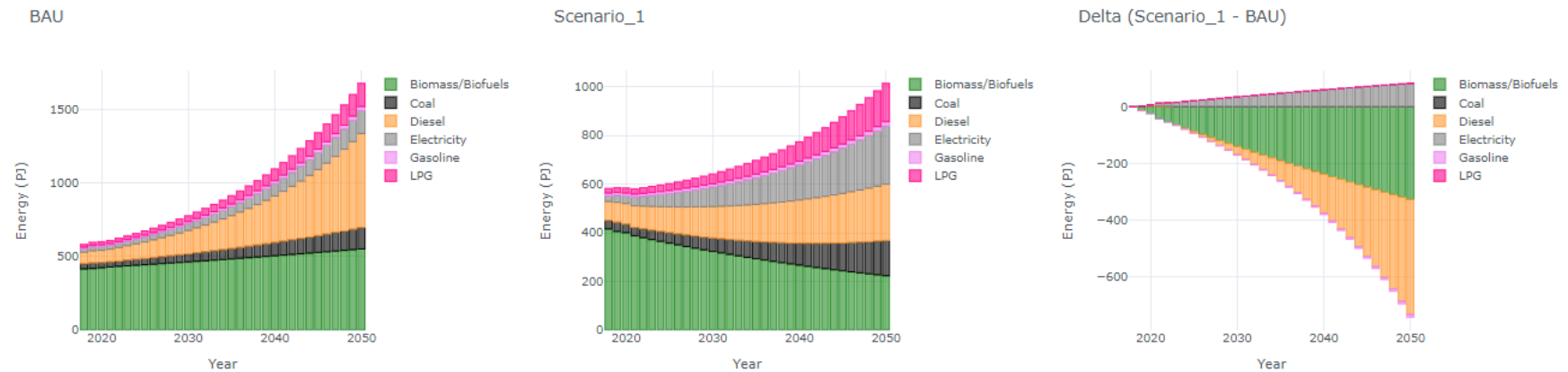


Figure 4.17: Comparison of gross final energy consumption by fuel

The energy requirement for biomass cooking and diesel and petrol-based transport has drastically reduced. It is observed that this reduction is compensated for by an equivalent increment in the consumption of electricity. By 2030, 35.26 PJ of additional electricity is required under scenario 1.

4.2.3 Comparison of power generation capacity

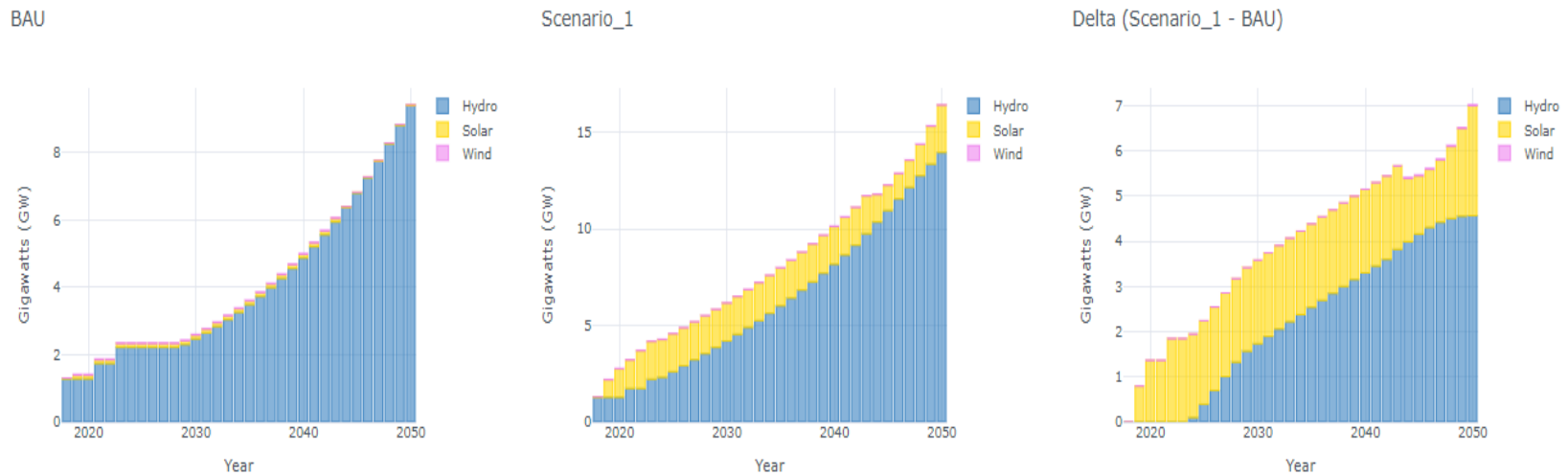


Figure 4.18: Comparison of power generation capacity

The power generation requirement will drastically increase as the demand for electricity increases in scenario 1. Here, 3.5 GW of extra power is required by 2030 and around 7 GW by 2050. The percentage of solar has also been increased as the model is more inclined towards energy mix under this scenario.

4.2.4 Comparison of domestic energy production

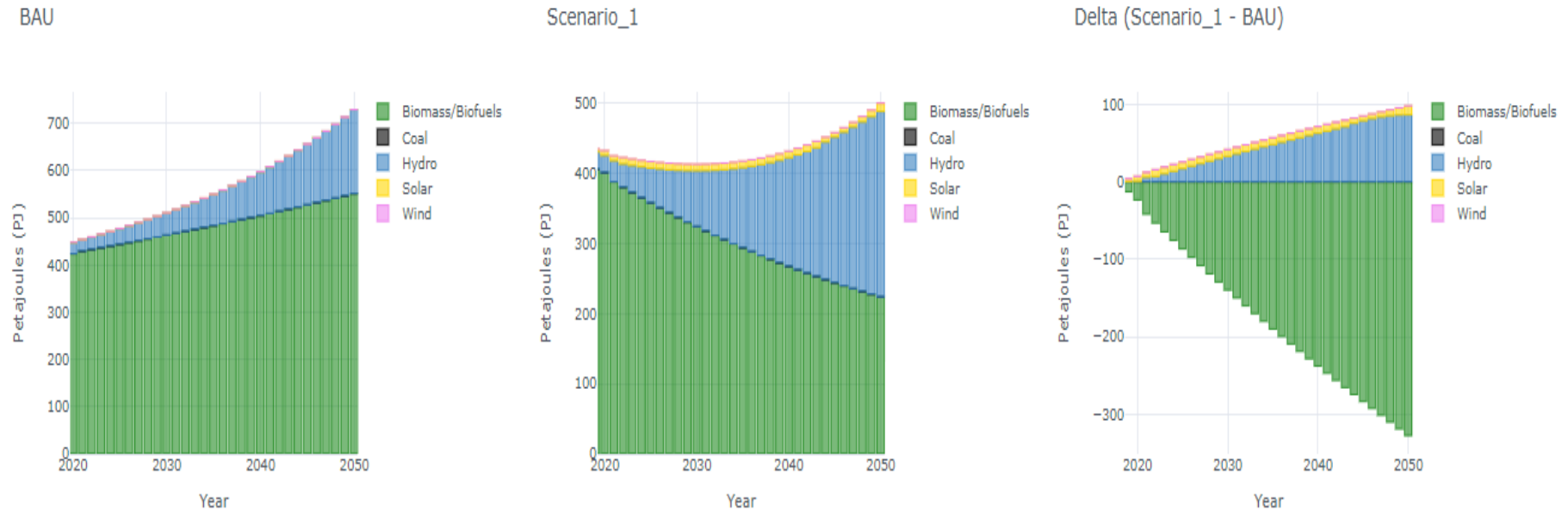


Figure 4.19: Comparison of domestic energy production

Here, the share of biomass in the form of domestic energy has reduced whereas the share of hydro and solar power has increased up to 100 PJ. This is because the wood fuel in residential cooking is being replaced by electric cooking and to meet that demand the country needs to produce more hydro electricity.

4.2.5 Comparison of energy imports

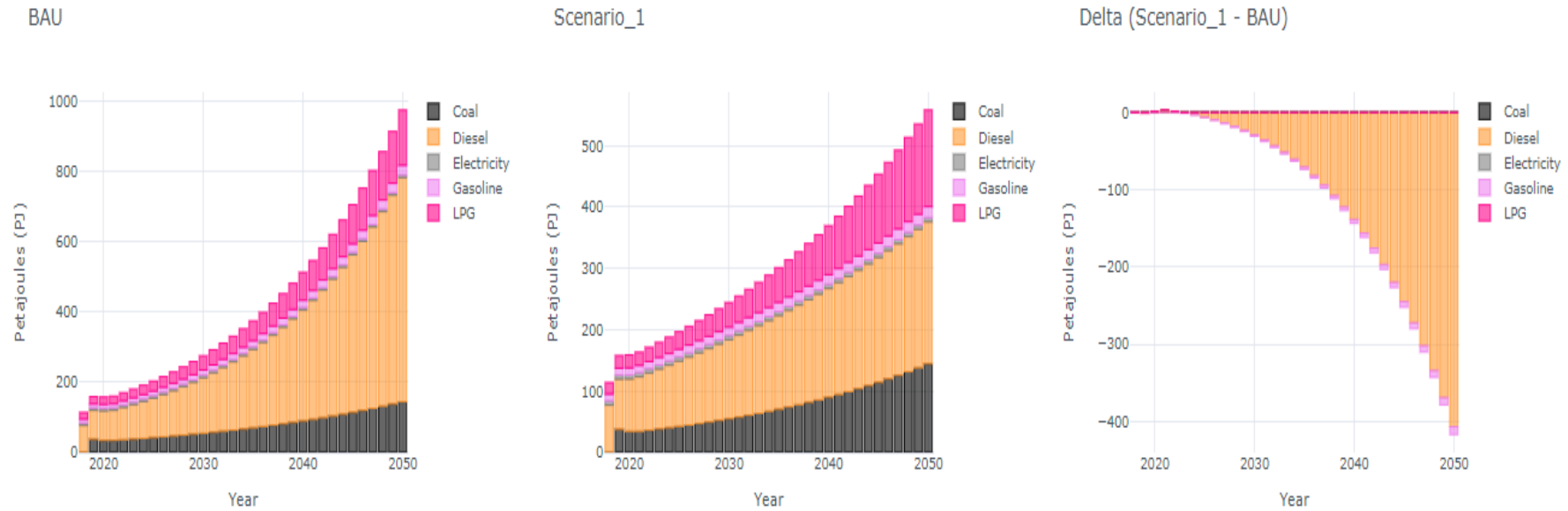


Figure 4.20: Comparison of energy imports

The demand for diesel and gasoline will reduce by almost 40 PJ by 2030 and around 400 PJ by 2050. Since, the demand of electricity is increased by the increase in the use of electric cooking and electric vehicle, it is obvious to decrease the demand of fossil fuel. The country can become independent of imported fuels only by adopting the means of electricity in residential and transport sector. The country can look for the more effective means of reducing the imports by giving more emphasis on import of electric vehicle and banning of old highly inefficient automobiles.

4.2.6 Comparison of water demand

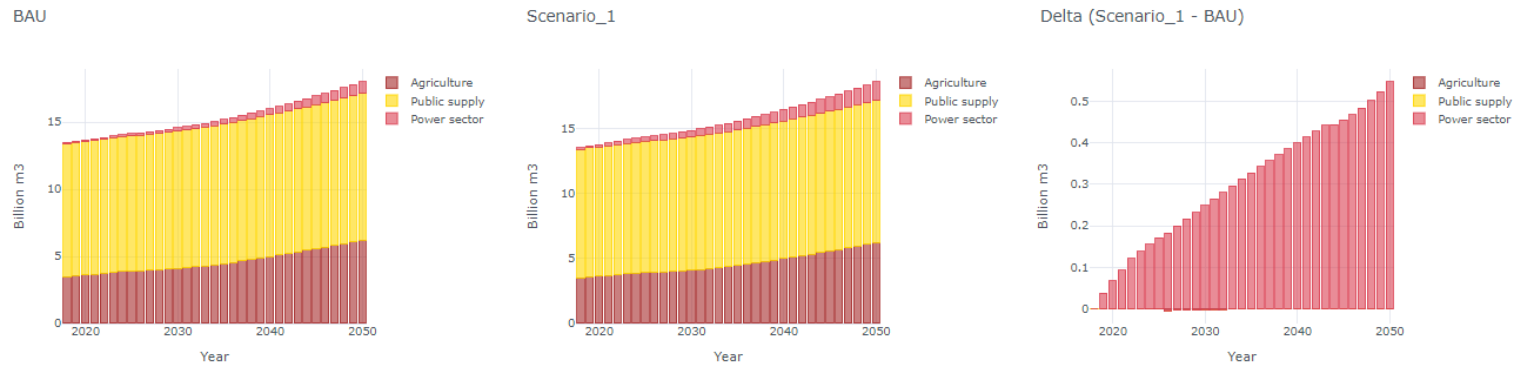


Figure 4.21: Comparison of water demand

The water demand on power sector will rise by around 0.25 billion cubic meter by 2030 and 0.5 billion cubic meter by 2050.

4.2.7 Comparison CO₂ emission by sector

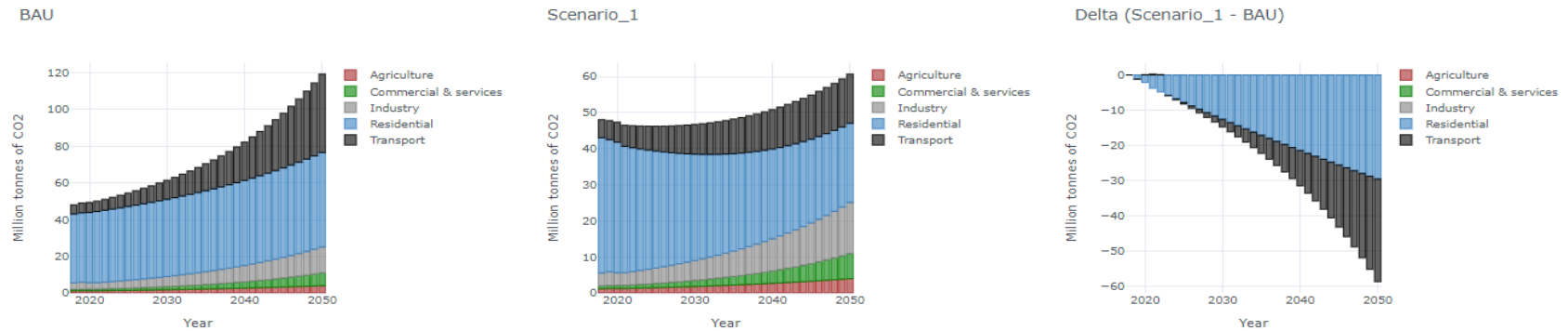


Figure 4.22: Comparison of CO₂ emission by sector

The NDC policy will reduce the CO₂ emission as targeted if implemented on point. The scenario will reduce almost 15 million ton CO₂ equivalent by 2030 where residential sector will have 12 tons and transport sector will have 3 ton reduction potential.

4.2.8 Comparison of CO₂ emission by source

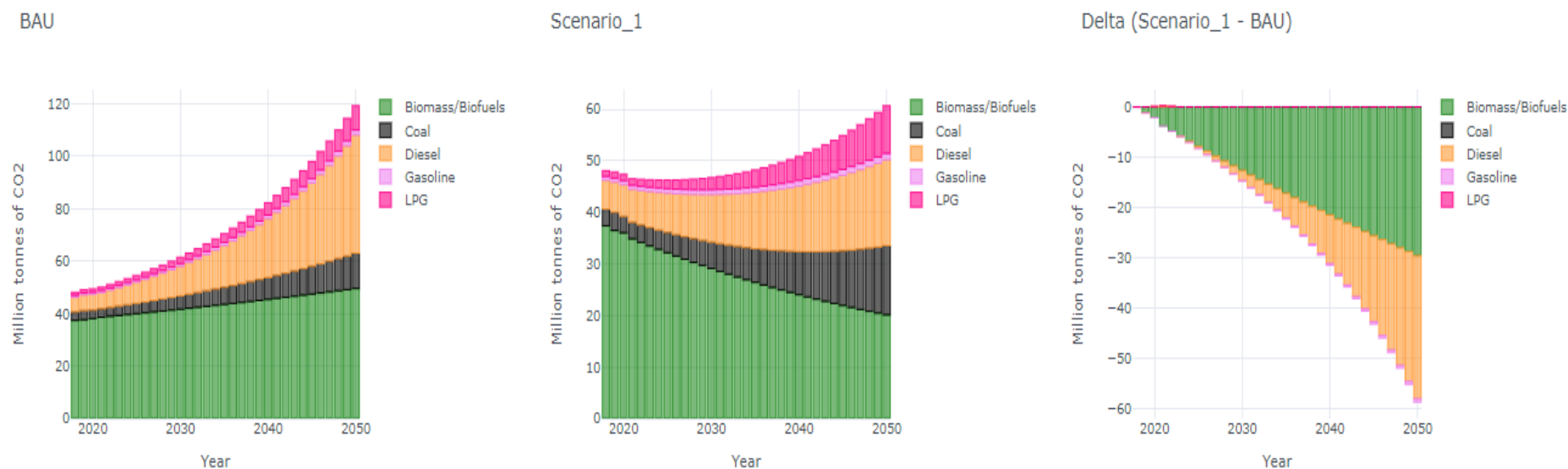


Figure 4.23: Comparison of CO₂ emission by source

The emission coming out from biomass and biofuels will drastically reduced upto 12 million ton and the emission form diesel and trasport will reduce upto 3 million ton of CO₂ equivalent by 2030. But, over a long run their contribution over emission reduction will be almost equivalent.

CHAPTER FIVE: CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

The following conclusions have been drawn from the study.

- The global demand for power is expected to increase significantly in the coming years, with a capacity requirement of 9 GW projected by 2050. In this context, hydropower is likely to be the most optimized source of power.
- However, with the increase in demand for power and fossil fuels, there is an increase in greenhouse gas emissions, with CO₂ emissions set to almost double, reaching 119 million tons of CO₂ equivalent. The major contributors to this increase in emissions will be the transport and biomass sectors, particularly the use of wood.
- Improved irrigated farming has the potential to double yields, as seen in the case of sugarcane. Additionally, forests can play an important role in sequestering CO₂ emissions.
- It is worth noting that the increase in power production will also have significant implications for water usage. The power sector alone will require almost eight times more water by 2050, while irrigation will require double the current amount. Overall, while the projected increase in power demand presents several challenges, there are also opportunities to pursue sustainable solutions and mitigate the impact of this growth.
- Similarly, the implication of NDC can contribute significantly to reduction of CO₂ emission and increment of hydroelectricity production for going towards electric in residential and transport sector.
- Under this scenario, the equivalent gross energy demand decreases by 135 PJ by 2030 whereas the power production rises by 3.5 GW including hydro and solar.
- Similarly, under the NDC scenario the import of fossil fuel demand will reduce by 40 PJ by 2030 and 400 PJ by 2050 A.D. The power sector will be requiring 0.22 million cubic meter water more and there will also be reduction of 15 million ton of CO₂ equivalent by 2030 A.D.

5.2 Recommendations

The following recommendations have been drawn from the study.

- The model has only considered the five types of crops, but further research and modelling can be done considering all the crops grown in Nepal.
- There is only one alternative scenario considered in the model so, for further research more alternative scenarios can be developed and compared.
- The CO₂ equivalent emission as per National Adaptation plan (NAP) in 2018 AD is 23 million tons however the model has calculated it to be around 45 million tons. The modelled data matches with the data from World Bank and USAID but it did not match with the NAP data. Further research needs to be done as the major reason for variation might be due to the mismatch of emission activity ratio.
- It is also essential to model the Nationally Determined Contributions (NDC) goals before setting the implementation strategy. Modelling in land energy and crops should also be done to ensure trade and food security.
- Furthermore, it is important for Nepal to consider electricity export, as optimizing the use of water resources will be essential for future sustainability.
- Finally, this model can be used to model any scenario for setting policies on the land, energy, water, and climate sector in Nepal. Further modelling and data collection is required which can ensure the roadmap of achieving the sustainable development and management of its resources in Nepal.

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APPENDIXES

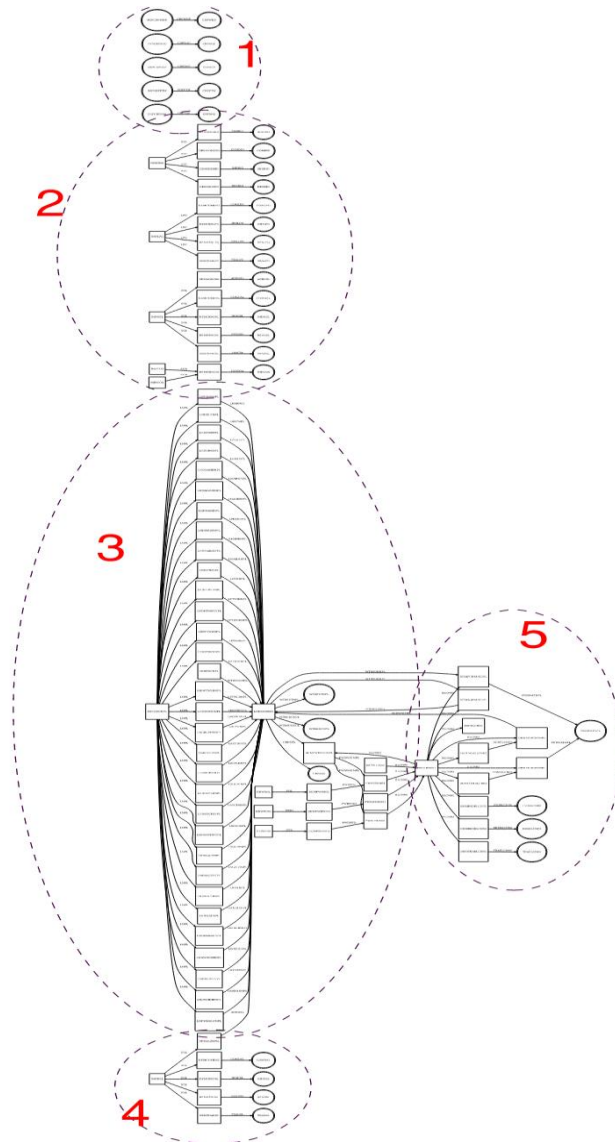
Appendix 1: List of commodities used in model.

| | | |
|-----------|------------|-----------|
| AGRBIO | LOTHNPL | WND |
| AGRDSL | LPG | WTREVTNPL |
| AGRELCN02 | LPTWHINPL | WTRGRCNPL |
| AGRGS | LPTWHRNPL | WTRPRCNPL |
| AGRWATNPL | LPTWIINPL | WTRSURNPL |
| BIO | LPTWIRNPL | |
| COA | LPTWLRNPL | |
| COMBIO | LRCPHINPL | |
| COMDSL | LRCPHRNPL | |
| COMELCN02 | LRCPIINPL | |
| COMGSL | LRCPIRNPL | |
| COMLPG | LRCPLRNPL | |
| CRPMAI | LSGCHINPL | |
| CRPPTW | LSGCHRNPL | |
| CRPRCP | LSGCIINPL | |
| CRPSGC | LSGCIRNPL | |
| CRPWHE | LSGCLRNPL | |
| DSL | LWATNPL | |
| ELCN01 | LWHEHINPL | |
| ELCN02 | LWHEHRNPL | |
| GSL | LWHEIINPL | |
| HYD | LWHEIRNPL | |
| INDBIO | LWHELRNPL | |
| INDCOA | PUBWATNPL | |
| INDDSL | PWRHYD | |
| INDELGN02 | PWRSOL | |
| INDGSL | PWRWATNPL | |
| INDLPG | PWRWND | |
| LBARNPL | RESBIO | |
| LBLTNPL | RESDSL | |
| LFORNPL | RESELCN02 | |
| LGRSNPL | RESGSL | |
| LMAIHINPL | RESLPG | |
| LMAIHRNPL | SOL | |
| LMAIINPL | TRADSL | |
| LMAIIRNPL | TRAEELCN02 | |
| LMAILRNPL | TRAGSL | |
| LNPL | TRALPG | |

Appendix 2: Fuel price

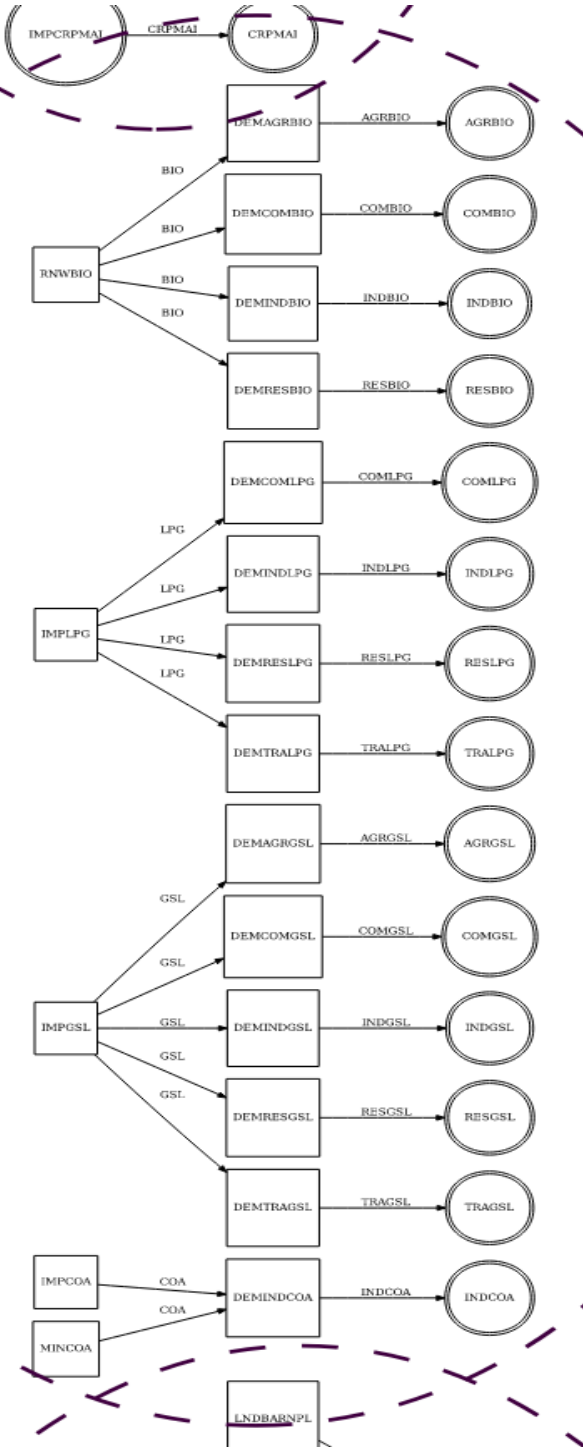
| Price (M \$/PJ) | 2018 | 2019 | 2020 | 2021 | 2022 | 2023 | 2024 | 2025 | 2026 | 2027 | 2028 | 2029 | 2030 | 2031 | 2032 | 2033 | 2034 | 2035 | 2036 | 2037 | 2038 | 2039 | 2040 | 2041 | 2042 | 2043 | 2044 | 2045 | 2046 | 2047 | 2048 | 2049 | 2050 |
|-----------------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|
| Fuel Wood | 3.112 | 3.168 | 3.225 | 3.270 | 3.315 | 3.361 | 3.406 | 3.452 | 3.497 | 3.542 | 3.588 | 3.633 | 3.679 | 3.735 | 3.791 | 3.848 | 3.904 | 3.960 | 4.015 | 4.069 | 4.124 | 4.178 | 4.233 | 4.291 | 4.349 | 4.407 | 4.466 | 4.524 | 4.586 | 4.648 | 4.711 | 4.773 | 4.835 |
| ATF | 31.428 | 32.057 | 32.685 | 33.380 | 34.075 | 34.770 | 35.466 | 36.161 | 36.930 | 37.639 | 38.468 | 39.237 | 40.006 | 40.857 | 41.708 | 42.559 | 43.410 | 44.261 | 45.202 | 46.144 | 47.085 | 48.026 | 48.968 | 50.009 | 51.051 | 52.092 | 53.134 | 54.175 | 55.328 | 56.480 | 57.632 | 58.784 | 59.937 |
| Coal | 5.165 | 5.211 | 5.257 | 5.305 | 5.353 | 5.401 | 5.450 | 5.498 | 5.548 | 5.599 | 5.649 | 5.699 | 5.750 | 5.802 | 5.855 | 5.908 | 5.960 | 6.013 | 6.068 | 6.123 | 6.178 | 6.233 | 6.289 | 6.346 | 6.404 | 6.461 | 6.519 | 6.577 | 6.637 | 6.697 | 6.758 | 6.818 | 6.878 |
| Gasoline | 36.206 | 36.930 | 37.654 | 38.455 | 39.256 | 40.056 | 40.857 | 41.658 | 42.544 | 43.430 | 44.316 | 45.202 | 46.088 | 47.063 | 48.049 | 49.029 | 50.009 | 50.990 | 52.074 | 53.153 | 54.243 | 55.328 | 56.412 | 57.612 | 58.812 | 60.012 | 61.211 | 62.411 | 63.739 | 65.066 | 66.394 | 67.721 | 69.048 |
| Diesel | 24.376 | 24.863 | 25.350 | 25.869 | 26.429 | 26.968 | 27.507 | 28.046 | 28.643 | 29.239 | 29.836 | 30.432 | 31.029 | 31.689 | 32.349 | 33.009 | 33.668 | 34.328 | 35.059 | 35.789 | 36.519 | 37.249 | 37.979 | 38.787 | 39.595 | 40.402 | 41.210 | 42.018 | 42.912 | 43.805 | 44.699 | 45.593 | 46.486 |
| Kerosene | 25.498 | 26.008 | 26.518 | 27.062 | 27.646 | 28.210 | 28.774 | 29.338 | 29.962 | 30.586 | 31.210 | 31.834 | 32.458 | 33.148 | 33.838 | 34.529 | 35.219 | 35.909 | 36.673 | 37.437 | 38.201 | 38.965 | 39.728 | 40.573 | 41.418 | 42.263 | 43.108 | 43.953 | 44.888 | 45.823 | 46.758 | 47.693 | 48.627 |
| LPG | 27.703 | 28.257 | 28.810 | 29.423 | 30.036 | 30.649 | 31.262 | 31.874 | 32.552 | 33.230 | 33.908 | 34.586 | 35.264 | 36.014 | 36.764 | 37.514 | 38.264 | 39.014 | 39.844 | 40.674 | 41.503 | 42.333 | 43.163 | 44.081 | 44.999 | 45.917 | 46.835 | 47.753 | 48.769 | 49.785 | 50.800 | 51.816 | 52.832 |
| Electricity | 28.247 | 28.499 | 28.752 | 29.006 | 29.266 | 29.527 | 29.790 | 30.055 | 30.322 | 30.592 | 30.865 | 31.139 | 31.416 | 31.696 | 31.978 | 32.263 | 32.550 | 32.839 | 33.133 | 33.427 | 33.724 | 34.024 | 34.327 | 34.633 | 34.941 | 35.252 | 35.566 | 35.882 | 36.201 | 36.524 | 36.849 | 37.177 | 37.507 |

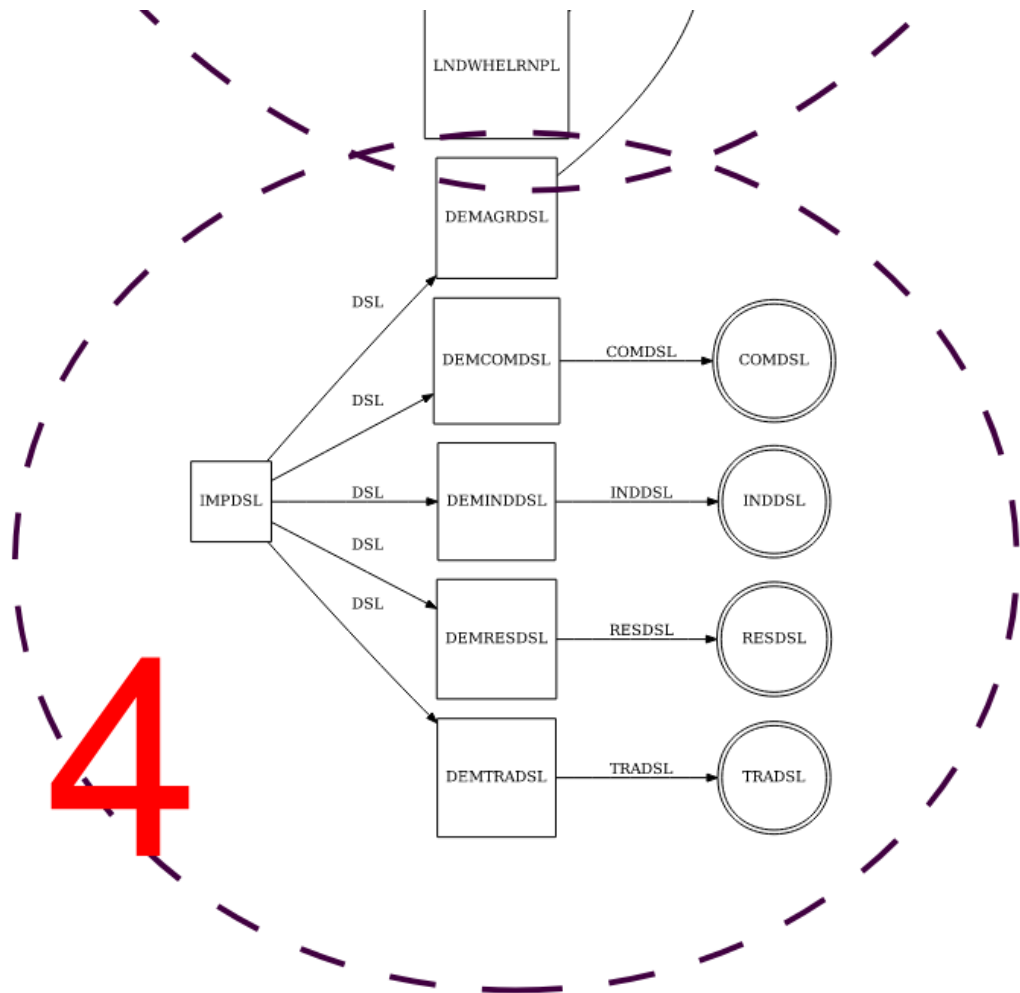
Appendix 3: RES of overall modelling system(Unzoomed)



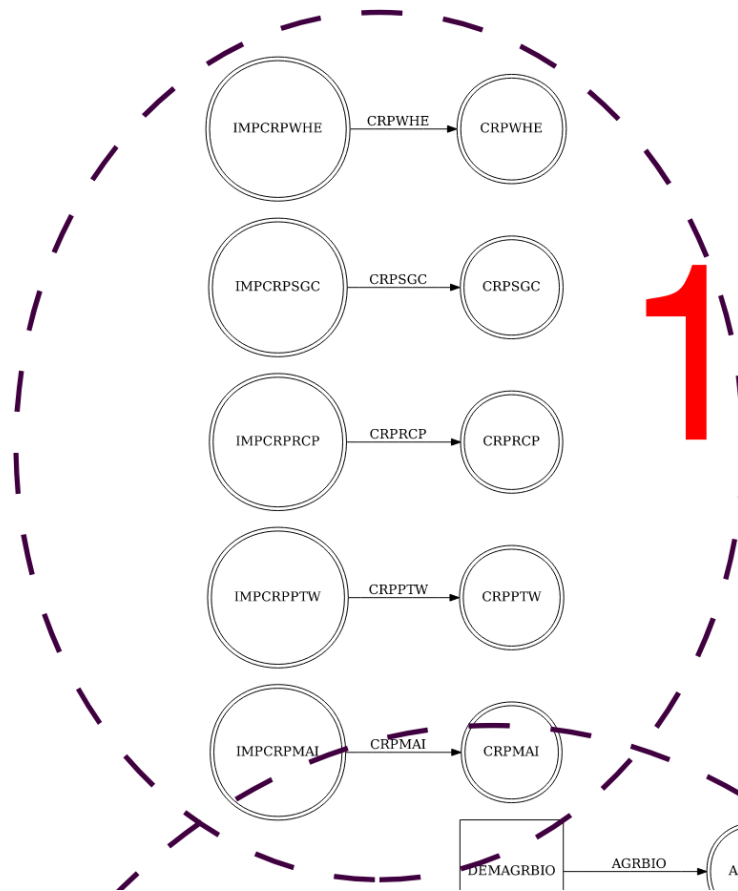
Appendix 4: RES for energy system

2

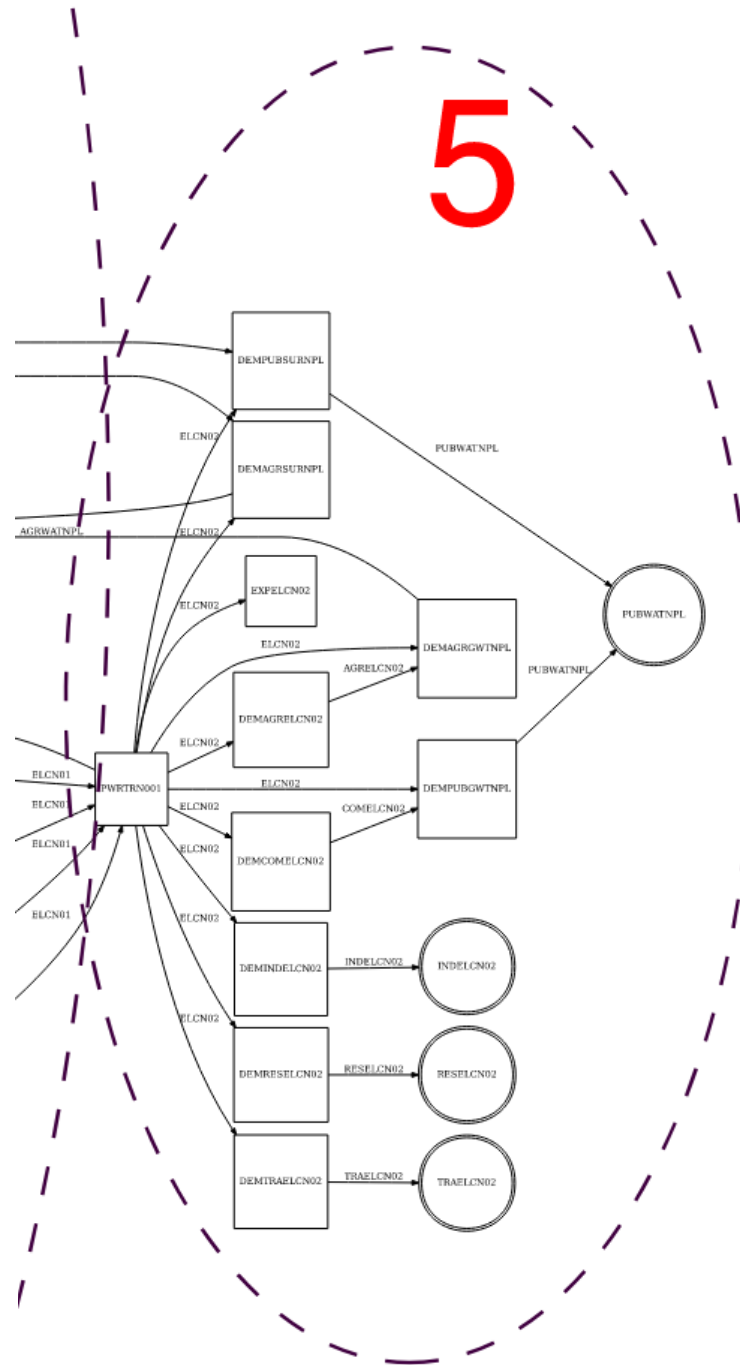




Appendix 5: RES for imported crops



Appendix 7: RES intorconnecting energy, water and land



Appendix 8: Yaml code for the model

The Yaml File code is as follows:

Model: Nepal_clewsmodel

Either otoole or MoManI (capitalization matters)

OutputFormat: MoManI

otooleOutputDirectory: otoole_output

Regions: {REGION1: ['Region 1', '#000000']}

Years:

- 2018

- 2019

- 2020

- 2021

- 2022

- 2023

- 2024

- 2025

- 2026

- 2027

- 2028

- 2029

- 2030

- 2031

- 2032

- 2033

- 2034

- 2035

- 2036

- 2037

- 2038

- 2039

- 2040

- 2041

- 2042

- 2043
- 2044
- 2045
- 2046
- 2047
- 2048
- 2049
- 2050

LandRegions:

- *NPL*

LandToGridMap: {

NPL: N

}

DataDirectoryName: data

ClusterBaseFileName: clustering_results_

PrecipitationClusterBaseFileName: clustering_results_prc_

EvapotranspirationClusterBaseFileName: clustering_results_evt_

IrrigationWaterDeficitClusterBaseFileName: clustering_results_cwd_

IntensityList: {

L: Low,

I: Intermediate,

H: High

}

IrrigationTypeList: {

R: Rain-fed,

I: Irrigated

}

LandUseCodes: {

BAR: Barren and sparsely vegetated land,

FOR: Forest land,

GRS: Grassland & woodland,

BLT: Built-up land,

WAT: Water bodies,

OTH: Other land

```

}
EvapotranspirationPercentPRCOtherLandUse: {
  # Percentages taken from Bolivia model
  BAR: 0.773,
  FOR: 0.691,
  GRS: 0.694,
  BLT: 0.631,
  WAT: 0.571,
  OTH: 0.694
}
GroundwaterPercentofExcessOtherLandUse: {
  BAR: 0.009,
  FOR: 0.077,
  GRS: 0.051,
  BLT: 0.072,
  WAT: 0.017,
  OTH: 0.051
}
# Percent of excess water (Irrigation + Precipitation - Evapotranspiration) that returns
as groundwater. Rest returns as Runoff.
GroundwaterPercentofExcess: 0.051
# Used value for grassland for now - may need to get a better number...
# Energy Structure
EndUseFuels: {
  IND: ['COA', 'LPG', 'GSL', 'DSL', 'BIO', 'ELCN02'],
  COM: ['LPG', 'GSL', 'DSL', 'BIO', 'ELCN02'],
  AGR: ['GSL', 'DSL', 'BIO', 'ELCN02'],
  TRA: ['LPG', 'GSL', 'DSL', 'ELCN02'],
  RES: ['LPG', 'GSL', 'DSL', 'BIO', 'ELCN02']
}

ImportFuels: ['COA', 'LPG', 'GSL', 'DSL',]
ExportFuels: []
DomesticMining: ['COA']

```

DomesticRenewables: ['WND', 'HYD', 'BIO', 'SOL']

Note: Transformation technologies assume that their fuels are created elsewhere (either in the DomesticMining, DomesticRenewables or ImportFuels.

TransformationTechnologies: [

['PWRTRN001', 'ELCN01', '1.176', 'ELCN02', '1', 'Power transmission', '1'], #15% of transmission system losses

['IMPELCN02', "", "", 'ELCN01', '1', 'Electricity import', '1'],

['EXPELCN02', 'ELCN02', '1', "", "", 'Electricity export', '1'],

['IMPCRPWHE', "", "", 'CRPWHE', '1', 'IMPORT WHE', '1'],

['IMPCRPMAI', "", "", 'CRPMAI', '1', 'IMPORT MAI', '1'],

['IMPCRPSCP', "", "", 'CRPSCP', '1', 'IMPORT RCP', '1'],

['IMPCRPPTW', "", "", 'CRPPTW', '1', 'IMPORT PTW', '1'],

['IMPCRPSPGC', "", "", 'CRPSPGC', '1', 'IMPORT SGC', '1']

Structure of data is: [Tech, InFuel, IAR, OutFuel, OAR, Name, Mode]

If the FUEL is "" that piece will not be created.

Name is used only the first time this technology shows up. Fuels are created only if needed.

If multiple lines for the same technology, this technology will have multiple input and output activity ratios.

Note: This section can also be used to add input or output fuels to various technologies (cooling water, for example)

]

Power Plants:

PowerPlants: {

PWRHYDN01: ['Hydro_existing', 1, 0, 0],

PWRWIND01: ['Future-WIND PP', 1, 0, 0],

PWRSOLN01: ['PV Utility scale PP', 1, 0, 0]

}

Emissions: {

CO2: ['Carbon dioxide equivalent emissions.', '#000000']

}

Timeslices: {

SEA1BAS: ['Season 1 baseload', '#000000'],

SEA1INT: ['Season 1 intermediate', '#cc9900'],

```
SEA1PEK: ['Season 1 peak', '#00cc66'],  
SEA2BAS: ['Season 2 baseload', '#ffffcc'],  
SEA2INT: ['Season 2 intermediate', '#99ff66'],  
SEA2PEK: ['Season 2 peak', '#cc3333']  
}
```

```
CropYieldFactors: {  
  WHE: 0.785564744,  
  PTW: 2.850425937,  
  RCP: 0.813409747,  
  SGC: 8.510494403,  
  MAI: 0.785564744
```

```
}
```

```
NamingConvention: {  
  IND: 'Industry',  
  RES: 'Residential',  
  COM: 'Commercial',  
  AGR: 'Agricultural',  
  TRA: 'Transport',  
  OTH: 'Other',  
  BIO: 'Biomass',  
  COA: 'Coal',  
  CRU: 'Crude oil',  
  DSL: 'Diesel',  
  ELCN01: 'Electricity from power plants',  
  ELCN02: 'Electricity from transmission',  
  GSL: 'Gasoline',  
  HFO: 'Heavy fuel oil',  
  NGS: 'Natural gas',  
  KER: 'Kerosene',  
  LPG: 'LPG',
```

OHC: 'Other hydrocarbons',
GEO: 'Geothermal',
HYD: 'Hydropower',
SOL: 'Solar',
WND: 'Wind',
CHC: 'Charcoal',
PCK: 'Petroleum coke',
JFL: 'Jet fuel',
ELC: 'generic electricity for import and export',
MAI: 'Maize crop'
}

Source: of script: *T. Niet and A. Shivakumar (2020): clewsy: Script for building CLEWs models.*

Appendix 9: process to cluster crop water data

Downloading the files environment and conda

- 1 Download the code zip folder named *Un-clews-gis-work-main* for clustering from [here](#) and put it in C drive. This folder contains code file, environment file raster input folder and the country folder for the inputs and outputs for Srilanka. We should only change the name of country and input as per the country we are going to do clustering.
- 2 Inside the un-clews-gis-work-main, there is folder called lka for srilanka, we need to rename it with the country that we want to do clustering for. The naming should be done as per the UN ISO 3 letter ISO country code. The inputs that need to be changed will be explained in the later part.
- 3 Install conda on your computer followed by jupyter lab.
- 4 Run jupyter lab in conda typing jupyter lab and then you will be directed to jupyter lab local host server.
- 5 After this load the code CLEWs GIS Processing.ipynb in the Jupyter lab which can be found in the zip file downloaded in step 1.
- 6 The code contains all the necessary guidelines and steps necessary for clustering. This document will only help to get you the necessary files of our requirement for running the code.

Running On Jupyter lab

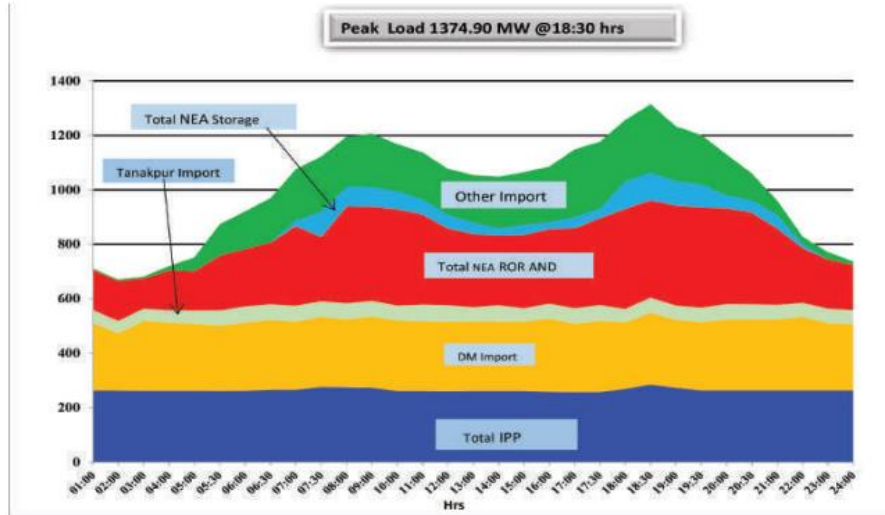
After you load the code in Jupyter lab you will see a stepwise instruction that you need to follow.

- 7 Create a necessary environment in conda to run the code in jupyterlab. The environment (yml) is found in the file you downloaded in preparation steps.
 - *Conda env create -f environment.yml* (where environment is the name of file which is *clews_gis_work.yml* in our case)
 - *Conda activate myenv* (By doing this the environment will be activated. For details please refer [here](#)).
 - If you could not create environment from the file then manually import all the modules in conda(which I did in my case).

- 8 After finishing import of necessary modules, we should give the input for name of area, crops and region, projection system and clustering types we want to study. The description in the code will guide you on how to select those things.
- 9 After this you need to set up the input and output file directory. The zip file downloaded in step 1 already contains those directories so no need to worry about that. The Zip file originally contains folder for Sri Lanka with ISO code *lka*. Now, all we need to do change the name of the file as per the UN ISO 3 letter country code for the country of our study and.
- 10 Now, in part 1 step 1 of the code you will require ascii grid file for the country. The ascii grid file which is already there in the input folder renamed in step 9 should be replaced by the ascii grid file that we require, and the name should be changed accordingly. The ascii grid file can be found here. But this step can be omitted if you already have a tiff file for that.
- 11 In part 1 step 2 of the code, you require admin level data file in gpkg format which can be downloaded here as per our requirement. (Download the file and place it inside the folder that you rename in step 9. Place it inside input folder and rename it looking at the example of Sri Lanka. The file name format is countrycode_adm0.gpkg where admin level can be 0, 1 or 2 based on our clustering input)
- 12 Now in part 2 of the code, we need to give input raster file for the code to read. The input raster file can be downloaded from SFU vault(GAEZ processed data and LC Type). Download the required files(tiff format) and put inside the global_raster_input directory of the folder downloaded in step 1.
- 13 Now, after setting up all these files correctly in the folder, all we need to do is run the code step by step in the Jupyter lab.
- 14 After the run is complete, the clustered output data will be generated in the output directory under the name of the folder created in step 3. of this section.

Appendix 10: system load curve and capacity balance diagram

**System Load Curve (Dry Peak Demand) Poush, 27,2076
(Jan 12, 2020)**



Capacity Balance (MW) in FY 2076/77 (2019/20)

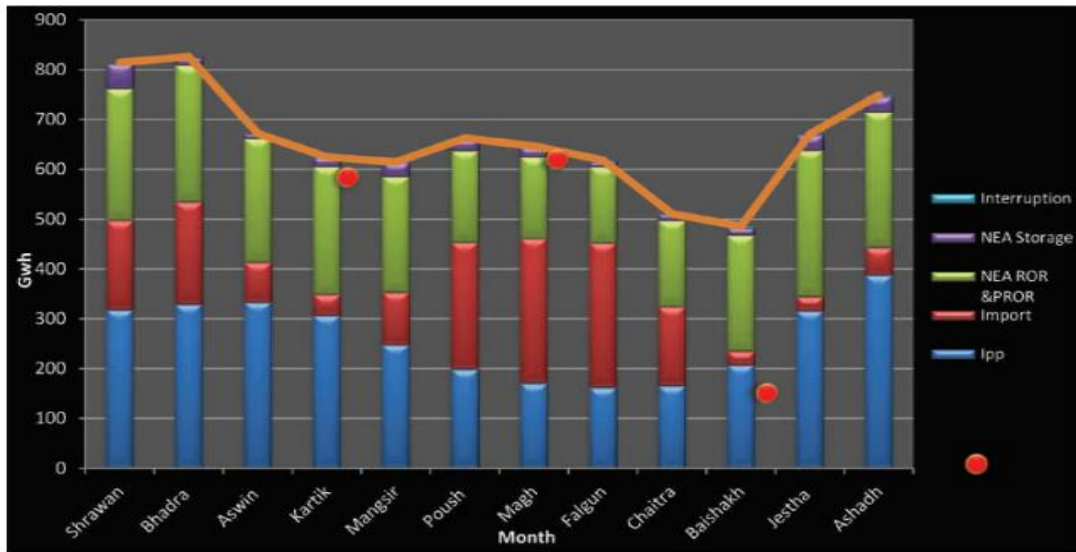


Figure: Energy balance in FY 2019/2020 from NEA annual report 2019

Appendix 11: Plagiarism check sheet

develop RES (Reference Energy System) for Climate, Land, Energy and Water nexus and optimize those to build CLEWs model for Nepal

ORIGINALITY REPORT

18%

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