EVALUATING THE POTENTIAL OF ADOPTING A WATER-ENERGY-FOOD NEXUS APPROACH TOWARD SUSTAINABLE DEVELOPMENT: A CASE STUDY FROM BANGLADESH

A Thesis

by

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ABSTRACT

In pursuance of continuous economic development, Bangladesh has undertaken a couple of long-term plans, namely Bangladesh Delta Plan 2100 and Power System Master Plan 2016, to buttress its productivity in agriculture, energy, and industrial sectors, which are aligned with the United Nations Sustainable Development Goals (SDG). In this study, the development endeavors of different ministries associated to water, energy and food of Bangladesh, projected for 2030 and 2041 was studied using Water-Energy-Food (WEF) nexus approach. Using the local resource usage characteristics of Bangladesh, a scenario-based assessment tool was developed following the 7 Question Guideline (7QG). It was found that either of the national priorities or global SDG indicators corresponding to food self-sufficiency, emission from energy and fresh water withdrawal, are hardly achievable with the limited internal water and land resources available. After carefully inspecting the trade-offs and synergies in water-energy-food cross-sectoral resource interactions, a set of scenarios, comprising of existing policy planning to alternative planning, has been developed for a comparative representation of highly connected to silo policy planning. Assessments from each scenario have been traced to national priorities and global SDG indicators to demonstrate which scenarios project more significant achievement of national goals. Unattainable scenarios were filtered following Socio-Technical-Economical-Political (STEP) 3 filter methodology. Feasible scenarios have been mapped back to the policies and connected ministries to point out the demanding coherency required for the implementation of such scenarios. Critical and potential interconnections

among resource subsystems have been identified to point out the resource hotspots, stress, trade-offs, and synergies to explore future policy recommendations.

CONTRIBUTORS AND FUNDING SOURCES

This work was supervised by a thesis committee comprising of Professor Efstratos Pistikopoulos of Artie McFerrin Department of Chemical Engineering, Professor Kent E. Portney of Department of Public Administration and Service and Bassel Daher, Adjunct Assistant Professor of Department of Biological and Agricultural Engineering.

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1. INTRODUCTION

1.1 Problem Statement: Background

The Sustainable Development Goals, declared by the world leaders in 2015, provides a blueprint to world communities for holistic development, in the biophysical, economic and social dimension, containing a set of 17 goals and 169 associated targets to embark on a new path for ensuring better life within the period of 2015-2030, leaving no one behind. The realization of a new set of goals was challenging based on the priorities of different countries with diverse economic conditions and the interlinkage of the associated goals among themselves (Nilsson et al., 2016). This scenario had added attention to spur research and has given rise to a number of tools to analyze interlinkage across a wide range of goals and targets through network analysis of water-energy-food nexus, urban systems, and co-benefit approach (Zusman et al., 2017). The water-energy-food interaction is interpreted as a set of interconnections of different resources or subsystems might vary from country to country, depending on its practice and policy of exploiting resources (Hoff et al., 2011; Mohtar and Daher, 2012; Lanford, 2019). On the other hand, noble approaches such as clustering of goals and targets across related themes, means of implementation of related goals (Niestroy, 2016), scale of interactions in terms of synergies and trade-offs have been demonstrated to understand the interlinkage across the goals and associate targets (Nilsson et al., 2016; Zelinka and Amadei, 2017). The International Council for Science (ICSU) adopted Nilsson's approach with a more in-depth review of interactions at the goals and target levels (ICSU, 2017).

However, economic growth and development are one of the central motives for under-developed, least developed, developing countries, including the developed countries, which influence the governments of these countries to adopt "business first" policies. The underdeveloped and least developed countries are more dependent on the bio-physical resources for economic activities and growth. If the SDG target network is framed in terms of interaction within these resources and other sustainable development goals, it is conspicuous that water, food, energy, with consumption patterns of these resources are the most influential factors in achieving SDGs and associated targets (Zhou and Moinuddin, 2017). In IGES 2017 report, it shows how each country, from underdeveloped to developed, have impactful and robust interlinkage among food, water, and energy usage. That is why it might be a prudent way to see how the endeavor of achieving economic growth interacts with water-energy-food nexus according to national planning and policy mapping as well as develop a tool to quantify impacts of a natural intervention or national priorities. For example, Mitra et al. (2017) showed partial improvement in water use efficiency in India has shown savings in water resources, electricity requirement, and reduction in CO_2 emission while maintaining a significant increase in GDP (Zusman et al., 2017). Occupying an area compared to one-fifth of the state of Texas with a population close to half of the United States, Bangladesh is one of the densely populated and most water using countries of the world. Since, the last decade, Bangladesh has experienced continuous economic growth closer to 7% (WESP 2019). The country has envisioned attaining the status of a middle-income country by 2021 and a developed country by 2041. Numerous policies and long-term plans have been formulated to buttress this endeavor and related policies are changing to engage people and resource towards increased economic activities, which demands more resources, in a limited landscape and scope. Perhaps, the most comprehensive planning are the Delta Plan Bangladesh 2100 and Power System Master Plan 2016 (PSMP) (MoPEMR, n.d.). These long-term planning have the same motivation, ensure maximum use of limited resources to achieve the socio-economic goals of Bangladesh. Numerous studies have shown the existent of strong correlation between per capita energy consumption and the Human Development Index (HDI) (Martinez and Ebenhack, 2008). Similarly, water, as an essential resource for agricultural production, industrial and household usage, has been addressed in the delta plan 2100. Food security is one of the prime concerns of Bangladesh, to meet the demand of growing population as well as maintaining production resilience against climate change. Bangladesh has also declared its national priorities, National Priority Indexes (NPI 39+1) in the commitment of achieving sustainable development goals by 2030 (NPI, 2019). In order to support its desired economic boast, Bangladesh will have to increase its food production, water resources by 50%, according to world standard (Parry, 2012) and energy resources by 150% (PSMP 2016). A co-riparian country with conflict in water sharing of trans-boundary rivers, being vulnerable to climate change and having limited energy resource to exploit and land to grow food, formulating planning and policies through unilateral impact analysis might be costly and irreversible in long run (Samaranayake, 2016).

Although, Bangladesh has shown tremendous achievement in food production in last couple of decades (Deb, 2011), it has been lagging behind in securing safe drinking water coverage compared to its neighboring countries (Kolas et al., 2013). Traditional farming in Bangladesh is becoming more dependent on ground water usage while increased industrialization keeps polluting the surface water (Qureshi et al., 2015). Moreover, the country has envisioned to shift its primary energy dependency from natural gas to coal, which is not only hazardous to environment but also thirsty way of generating electricity (PSMP 2016; Chowdhury, 2017). However, it is conspicuous that availability of energy aids to increase the living standard of people, it might promote people to adopt wasteful practices in using limited natural resources such as water for growing food, manufacturing agricultural and non-agricultural products. Currently, Bangladesh is withdrawing more groundwater than its recharge capacity by wasting 32% of withdrawn underground water for agriculture (Hoque, 2018). Meanwhile, extensive dependency of underground water has led to the lowering of underground water label in growing cities which has contributed to arsenic poisoning in some parts of the country posing serious public health threat (University of Delaware, 2016). Dumping of solid waste in addition to annual sedimentation through water flow in rivers and flood, are contributing to the loss of depth of surface water reservoirs (Country Environment Analysis, 2018). In a nutshell, current policies and their execution process in silos and uneven connections might not be enough to attain country's long-term missions (Tett, 2015). In recent survey reports and SDG related documents produced based on data available from 2001-2014 about Bangladesh, it has been shown that the most critical and influential goals are associated with water, food production and energy generation as well as means of using these resources (Gain et al., 2015). In Bangladesh, water, as a resource, is essential for food, transportation and production whereas, energy is prerequisite for withdrawing and transporting water for agriculture and production. As a source, water has to rely on natural blessing, namely annual rainfall and water flow through rivers, and energy is aiding to extraction of more water thus quickly lowering the reserve. Under current situation, increased usage of energy has also led to increased industrial and agricultural production and pollution. Hence, Bangladesh is facing the development pollution followed by possible economic water scarcity (shown in fig. 1). Looking at the policies and planning of Bangladesh, it can be found that water related policies are more concerned about impact on water and environmental, rather than securing water resource (Gain et al., 2015). The national food policy and agriculture policy seem to be more focused on increasing production by emphasizing more on availability of water and energy for irrigation, but not for improving efficiency in using water (Islam, 2014). The environment policy and industry policy are also narrowly focused on reducing water pollution rather than limiting water usage for the sake of rapid economic development. The Power System Master Plan 2016 is directly focused on how it will be supporting the growing electricity demand for industrialization through burning coals rather than considering the direct or indirect impact on water and environment. Thus, policies, emphasizing their own goal and accomplishment, are unknowing working coercively to each other. The Delta Plan 2100 seems to address issues associated with water usage efficiency and management, but relevant policies seem lagging behind in adopting the plan. Such actions might lead to economic achievement in the long run, but might contribute to irreversible damages that can hinder the sustainability goal. The only interaction with water to energy was shown in the generation of hydro-electric power.

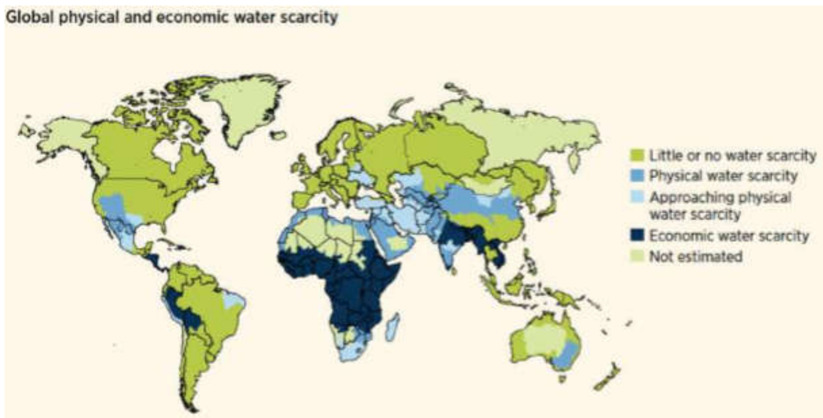

Figure 1: Global physical and economic water scarcity reprinted from WWAP (2012).

The sustainable development report 2019 pointed out how the SDGs are dependent and competing among themselves, thus blindly following the goals in national goal will also lead to conflicting issues (Sachs et al., 2019). If WEF nexus knowledge is screened through national priorities (NPIs) of Bangladesh government, it will be found that NPI 4- maintaining cultivable land, NPI-17 and 18 - ensuring 100% population using safe drinking water and sanitation facilities, NPI 19- ensuring 100% electricity coverage, NPI 21- annual growth rate of GDP, NPI 25-increase industry value-added activities and NPI 31- ensure industries installation for waste management system aiding and constraining each other due to their inherent dependencies. Perhaps, the only resource recovery priority among the aforementioned priorities is NPI 31, which might be constraining the free flourishment of water-thirsty agricultural practices and industrialization. With the gradual increase in population, industrialization, energy, and food demand, water is becoming a more indispensable resource in developing countries like Bangladesh. Being one of the most water using nations of the world, the national water security index of Bangladesh is 1.4 which is lower than the global standard (5) and drastic development endeavor without considering the interaction of resources might exacerbate the water security in the long run (Ganguly and Thompson, 2017). To meet the increasing energy demand for industrialization, agriculture and household, Bangladesh has planned to set more thermal power plants that have been criticized for its adverse impact on the environment and water (Islam, 2016). Coal-based power plant near world heritage site, the Sundarbans, and on the coastal areas of Bangladesh supposedly creates an irreversible ecological impact on coastal biodiversity and agriculture affecting the food security in near coastal areas irreversibly (Chowdhury, 2017). Thus, choices for energy production will have an indomitable effect on water and food as well. In attaining the MDGs, Bangladesh had performed significantly better than other UN members (Millennium Development Report, 2012). In drive of attaining SDGs, the government has to be more informed of exploiting available resources in terms of sensible use and resource recovery whereas current policies seem to be narrowly focused on outcome rather than application (Sachs, 2019). Development of WEF nexus knowledge is a learning process where the understanding can be improved through collaborative actions of concerned ministries and stakeholders and adjust/update their actionable process accordingly (Daher et al., 2018). Through better understanding of the interconnected resource systems, identifying trade-offs and synergies of a policy decision, better planning framework developed, investment and financial gains can be realized in terms of economic goals rather than over exploiting limited resources (Stephen et al. 2018). Thus, WEF nexus consideration can help to develop policy guidelines to maximize the financial, economic, social and environmental benefits across the sectors (Daher and Mohtar, 2015).

1.2 Objectives

The overall goal of this thesis is to quantify the impact of cross sectoral policies on finite natural resources namely water, food, energy and environment. This will include identifying synergies and resolving different trade-offs toward attaining SDG targets through realizing interconnectivity of intertwined resource network based on the prevailing practices of Bangladesh. The four objectives of this study are described as follows:

1. **Map** the policy interconnections, priorities and overlap between the Sustainable Development Targets and National Priority Indicators in Bangladesh.
2. **Develop** a water, energy and food interconnected network based on sectoral usage, local characteristics and identification of most critical and potential interactions among resource subsystems and policy interdependencies.
3. **Develop** an analytical tool to quantify the resource requirement, trade-offs and synergies, associated with possible alternative scenarios for food, water, and energy sectors by 2030 and 2041.
4. **Develop** a list of recommendations for better policy coherency.

2. LITERATURE REVIEW

2. 1 Understanding Inherent Interlinkage of Resource Subsystems

2.1.1 Terminologies

Nexus, by definition, refers to connections linking different elements (Gareth and Graham, 2019). The concept of tight interconnectedness across resources, water, land, food, energy, and environment, has been gaining increasing attention in the research and decision-making communities (Garcia and You, 2016). The original nexus concept looked at the water security of water, energy, and food supply from the water perspective (Hoff, 2011). However, the popularity of the nexus model can be traced to the World Economic Forum in 2008, where the global challenges related to economic development were recognized from the water-energy-food nexus (WEF nexus) perspective (Zhang et al., 2018). According to the Global Risk 2011 report, the water-food-energy nexus is highly influential in preserving human, social, and political security. The urgency of identifying interlinkage on thematic focus areas of SDGs has been growing since the declaration of Agenda 2030, leading towards the creation of working group under Inter-Agency and Expert Group on SDG (IAEG-SDG) by United Nations. Despite such importance on WEF nexus, imposed by international organizations, the core concept of nexus representation of resources seemed to be seldomly recognized by developing countries (Gain et al., 2014). Notable researchers have also reported that the introduction of the WEF nexus concept is context-dependent; generalized use of such terms can be overlapping and ambiguous (Benson et a., 2015; Cairns and Kryzywoszyska, 2016). The term WEF has been represented differently from the perspective view of the principal component of a nexus framework as the term brings a different meaning to different stakeholders (Alluoche et al. 2015). It can vary around Energy-Water-Food (EWF), Food-Energy-Water (FEW), or Water-Energy-Food (WEF), based on the focus of research or interest of stakeholders (Liu et al. 2018). The scope can be broad, covering economy, resource security, climate, or as narrow as a defined system where only a few interconnections among resources are selected (Pandey and Shrestha, 2017).

2.1.2 Global Trends

Although the definition and structure of nexus modeling have been varying due to variation in context and research environments (Keskinen et al., 2016), there are essentially two broad categories of nexus consideration. In the first category, the nexus is interpreted as interconnections among different resource subsystems within the nexus systems (Sanders and Webber, 2012). This approach aims to identify trade-offs and synergies of resource systems, internalize social and environmental impacts, and guide the development of cross-sectoral policies (Albrecht et al., 2018). The interconnection process among these resources includes physical and chemical relation, input and output relation, interaction with external factors such as market, governing institution, and security issues (Cai et al., 2018). For instance, food production demands water and energy in forms of tillage, fertilizer, chemical, and irrigation; water extraction, purification, and distribution require energy to complete the water life cycle; energy extraction and processing demands water (Daher et al. 2018). In the latter category, the nexus is presented as an analytical approach to quantify the functionality of the link or identify the impact or influence of interlinks (Zhang et al., 2018; Zelinka and Amadei, 2017; Nilsson et al., 2016). The Food and Agriculture Organization showed how the coupled behavior of human and nature could be integrated in the management of natural resources through nexus approach (FAO, 2014). Despite differences in methodologies in the categories mentioned above, both approaches can provide a framework for better decision making in resource governance by addressing trade-offs and identifying synergies in WEF nexus.

2.1.3 Existing Models

The model of WEF nexus depends on both geographic scales and focus of the study. The scale can vary from city to global level. The focus of the model can be a combination of only core elements; water, energy and food, to elements affected by the core elements; land use, emission, climate, ecosystem and economy. Moreover, each model can be different from other in terms of model type (quantitative, simulation, statistical and integrated), purpose (case study or scenario assessment), temporal variation (present and future), data availability (limited, moderate or high) and to support stakeholders of such research outcome (Dai et al. 2018). The complexity of tools representing each model is dependent, mainly on the research objective. The Climate, Land-use, Energy, Water (CLEW) framework, is one of the most comprehensive nexus tools, developed by the International Atomic Energy Agency (IAEA) and reviewed by IRENA for national scale assessments. To achieve a specific goal, the tool provides information on synergies and trade-off in CLEW areas to the decision-makers (Howells et al., 2013). But the tool is very data-intensive and involves multiple planning tools. Limitations in data can reflect to critical gaps from the actual modeling. Tools such as MARKAL/TIMES, MuSIASEM and WEAP (Water Evaluation and Planning)-LEAP (Long Range Energy Alternative Planning System) focuses in complexity in modelling specific nexus areas. MARKAL/TIMES tool are useful for energy modelling, but model accuracy depends on quality of data. WEAP-LEAP, as a computational tool is very much data intensive and energy centric (SEI, 2013). MuSIASEM model includes socio-economic indicators as an essential part of the model along with technical perspectives (FAO, 2013). However, the model is data and tool intensive and lacks cost-benefit assessments (Daher and Mohtar, 2015). Transboundary modeling frameworks, such as WaterGAP model (Guillaume et a. 2015) and BRAHEMO (Yang et al. 2016) are water centric, assumption intensive and data dependent model frameworks (Albrecht et al., 2018). On the other hand, NexSym is a simulation-based tool, which fits to model local resource system where dataset specific to local context is crucial (Hernandez et al. 2017). The Water-Energy-Food Nexus Tool 2.0, developed at Texas A&M University, is scenario-based assessment tool to quantify the resource requirements associated with different scenarios for water, energy, and food portfolios (Daher and Mohtar, 2015). Each scenario is converted into input variables as the tool calculates net resource requirements and an overall sustainability index. The sustainability index serves as a comparison between different alternative scenarios. The tool bypasses the need of extensive data and objectively compares policy alternatives. Scenario based computational models can provide the ability to test feasible options that connects nexus assessment. However, the assessment of the tool is very time specific and does not include any computation on future projection.

2.1.4 State of the Art Research Questions

WEF nexus models are often case-specific, where resource interactions are defined based on contextual factors such as local geography, climate, economy, socio-political situation, resource demand or national goals. Thus, development of model involves integration of physical, technical, social and economic contexts of the nexus. Researchers often adopt mixed method approaches, combining quantitative and qualitative method to attain more holistic understanding of the WEF system (Guillaume et al. 2015). This new trend of research is trying to identify nexus trade-offs by focusing on critical, social, and political dimension of resource security.

2.1.5 Data Gaps

In spite of different methodologies, development of nexus model requires to address an integrated management of three sectors by cross-sector coordination in order to reduce unexpected sectoral trade-offs and promote the sustainable development of each sector. In this regard, it differs from conventional decision-making practices that are previously considered within separate disciplines (Liu et al., 2015; Daher et al., 2018). But nexus modelling has a few intrinsic and extrinsic challenges:

1. *Mapping an appropriate nexus model:* Thorough identification and understanding on the resource interdependencies, interconnection, trade-offs, cross efficiencies and synergies among water, energy and agriculture sectors within a geophysical boundary. (Rodríguez et al., 2013; Hoff, 2011)
2. *Nexus database and data scarcity:* To develop an analytical framework for synergy and trade-off analysis, the complexities in developing formulas based on the context of countries and actual data to predict impact of a policy decision or guide implementation. (Hoff, 2011; WEF, 2011; Bizikova et al., 2013; WWAP, 2014)
3. *Proper tool and methodology:* Based on prevailing condition of a country, proper tool and methodology in modelling the nexus with inclusion or exclusion of further resource in the nexus system, development of resource accounting tools, modelling resource life cycles. (Hoff, 2011; WWAP 2014), identifying physical and technical variables and their trends (Rodríguez et al., 2013).
4. *Absence of policy and regulatory coordination:* Nexus modelling developed so far has put recommendation based on physical and technical issues of resource system, but did not look into the ways on how the government can implement the knowledge successfully.

5. *Stakeholders' awareness:* Nexus approach does not analyze the impact of absence of policy decision or consumers' preference on a prescribed solution. It is completely a computational tool. Thus, absence of stakeholders' awareness due to the lack of information and communication vehicles that connect society to the government and scientific discussions, challenges and concerns. This information - communication gap

hinders wider emergence and adoption of responsible consumer responses. Moreover, emerging nexus methodologies have diversified drivers and dimensions, incorporating interdisciplinary, participatory, physical and social aspects of resource system. Such development urges for deeper understanding of science, social and political context.

2.2 Characteristics of Water, Energy and Food Resources in Bangladesh

As mentioned in previous subsections, national priorities revolve around particular resources separately, seldomly considering the holistic interaction among resources. As the study concentrates on understanding how corresponding resources are connected. Not all resource systems all over the world are identical, resource are mostly influenced by local characteristics, for example, water uses for rice production is not similar all over the world, which is highly dependent on regional water availability. On the other hand, countries having a lot of fossil fuel-based energy reserve use a lot of water for pumping oil and gases. Thus, before identifying interconnection and interdependency among resource subsystems, it is pertinent to understand the local characteristics resource inflows and outflows among resource subsystems.

2.2.1 Water Resources

With more than 700 rivers flowing through the landscape, the supply of water resources is highly dependent on upstream inter-government strategies with neighboring countries. 91.3% of total fresh renewable water (1,122 BCM/year) comes from transboundary rivers of upstream India, China, Nepal and Bhutan. The water resources are not abounded and distributed evenly throughout the country. With the increase of population density, the per capita water resources of Bangladesh are lower than international standards and has already exceeded the water scarcity threshold defined by Falkenmark. With the current water usage pattern, the country is projected to approach absolute water scarcity before 2030 (Gain et al. 2015). According to FAO 2013, the country has around 84 BCM and 21 BCM renewable surface and ground water resources respectively. The wet lands are mostly situated on eastern and southern part of the country. Major portion of the net water withdrawal from water sources are used in agriculture and fisheries, followed by industry, residential usage and ecology. The total amount of water being used in agriculture is increasing as the country eyes on achieving food self-sufficiency. According to recent climate change pattern, 'too much water' during wet season and 'too little' water during dry season has significantly shifted the dependency of agriculture on ground water (Gain et al. 2015). In 2008, 79% of the total water used in agriculture were withdrawn from ground which was beyond the national renewable ground water limit (20 BCM). The growing dependency of groundwater have been putting more stress on ground water availability on the agriculture rich north west part of country, causing lowering of ground water level and making more vulnerable to arsenic poisoning (Zahid 2015). Fig. 2 shows the sectoral water consumption in 2008 (FAO). The water demand is increasing in urban areas. In the capital and several municipalities, treated waste water facilities have been used for water supply. Some peri-urban agriculture also relies on such treated water. There are only a few desalination plants available in the southern part of the country which is responsible to supply drinking water in the locality. In most part of the country, people are still dependent on ground water resources for household usage. Most of the industries in Bangladesh are water intensive. Two growing industries, textile and leather are competing in securing water resources for industrial processes. With the current industrial growth rate, the textile sector will be needing 40% more water by 2030 (WRC 2030).

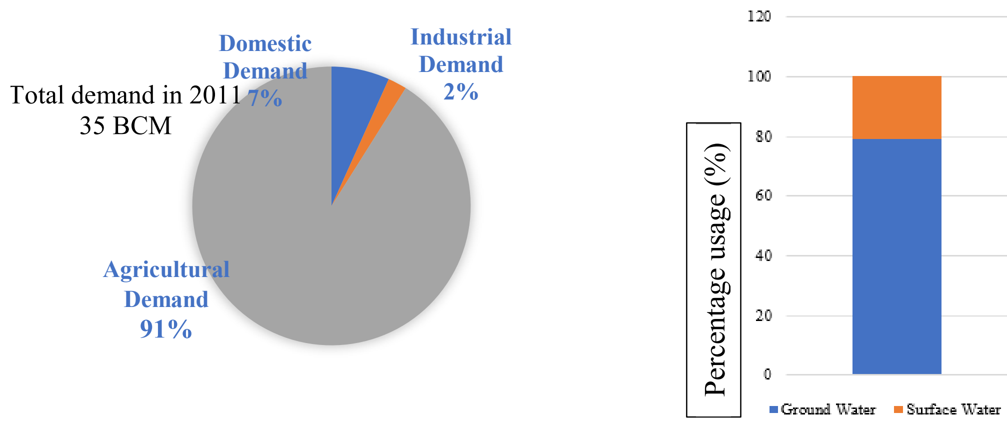

Figure 2: Sectoral water consumption of Bangladesh adopted from WRC (2015)

Due to absence of proper regulation in effect, the water pollution from industries has limited the surface water usage for agriculture. In addition, increased food production through intensifying agriculture creates significant impact on the quality of water bodies through agricultural runoff polluted with fertilizers, pesticides and manure from farms, fields and feedlots (Mirza and Hossain, 2005). So, stress on safe, usable surface water is also growing as food and industrial production intensifies.

2.2.2 Energy Resources

Bangladesh has lowest per capita energy consumption, 332.5 KWh, making it lowest energy consumer in the south Asian region. The country is dependent on its depleting gas, coal and oil reserves for its primary energy demand. Bangladesh has a very limited coal and oil reserves. The only operational coal mine is located in the northern part of the country, where the coal is used for electricity production. The gas is used being used for producing fertilizers, electricity and household purposes. Bangladesh is highly dependent on imported oil where only 11% oil is produced domestically. The extraction and processing facility is quite limited in the country. The gas is produced in traditional ways. The electricity production is highly dependent on domestic gas, coal and imported oil. The life time of gas run power plants are limited and projected to be phase out of the production one by one before 2030. According to PSMP 2016 and Power Cell of Power Division, Bangladesh has planned to shift its energy dependency from gas to coal in coming years. The country has already signed agreements with foreign development partners, India, China and Japan to finance 23 coal-based power plants in the southern region of the country with an aggregate capacity of 000MW. On a resource footprint perspective, coal-

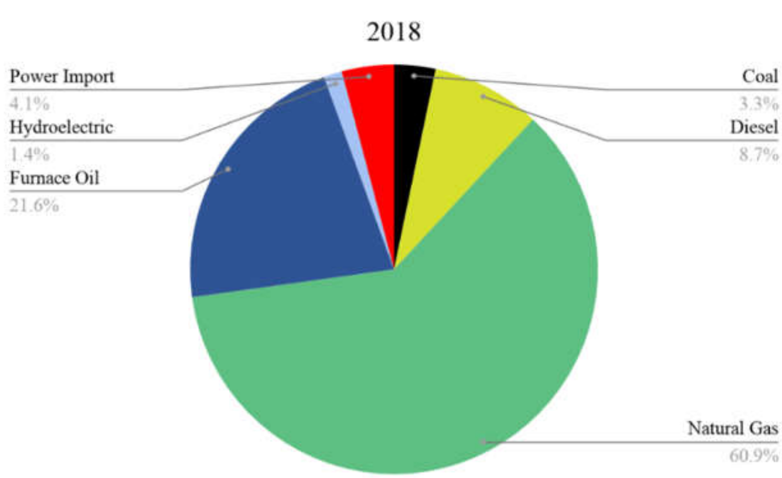

Figure 3: Energy mix in 2018 for electricity production reprinted from PSMP 2016

based power plant has higher carbon footprint compared to any other power generation technology. Fig. 3 illustrates the prevailing energy mix of Bangladesh. The country has also set two nuclear power plant, which will be in production stream by 2030 and 2041. Nuclear power plants are water and land resource intensive but cleaner source of electricity compared to fossil fuel. The country has the only hydro-electric powerplant at the south eastern region with generation capacity of 218 MW. According to PSMP, there are potential of setting a few small-scale hydro power plants due to flat terrain and low water head. Among the renewable energy sources, solar and biomass found promising and effective in the context of Bangladesh (Islam et al 2014). Still, Bangladesh is at nascent stage for using its full potential for renewable electricity generation. In the rural area, Biomass is extensively used as an alternative source for cooking, heating, crop processing and other household activities. Generally, biomass refers to rice husk, crop residue, jute stick, wood, animal waste, municipal waste etc. (Islam et al. 2014). It is the fourth largest source of energy in the country according to IEA. From environmental and economic sustainability point of view, biomass energy is the most effective form of energy. Bangladesh is endowed with rich biomass energy with a potential electricity generation capacity of 13830 Ktoe from agricultural crop residues, followed by 10400 Ktoe from recoverable waste, and 2494 Ktoe from fuel wood, saw dust and tree residues (Hassan and Badr, 2007). In spite of such potential, only one biomass based 250 MW power plant had been installed which is currently operating below minimum capacity. Geographical location of Bangladesh is considered as a favorable place for solar energy utilization. The annual solar radiation available here is over 1900 kW/m^2. Bangladesh receives approximately 69751 TWh/yr equivalent of solar energy which is over 500 times higher than nations total energy demand in 2016. Bangladesh is more accustomed to use renewables for off grid electricity generation. Out of its 625 MW installed capacity of renewable energy generation, only half of the energy is on-grid generation, dominated by solar and hydro-electricity. Bangladesh also lagging behind in utilizing wind power for energy generation. As the southern part of the country has the most favorable wind speed for converting it into electricity, extensive land demand for such facility limited its usage in contrast with other traditional and fossil fuel energy sources in spite of low carbon and water footprint.

2.2.3 Food Resources

As an important element to live, food is indispensable. According to FAO, wheat, beans, coarse foods and rice, considered as cereal foods, takes the larger share of the total food production in the world. In 2016, cereal based food consumption reached 40 million ton per year and the demand will keep growing in future. Food is required for industrial production, agro industries, feed the livestock and for human consumption. Cereal crop production, predominantly rice, are the mainstay of Bangladesh's agriculture, but yet, there is a sizable yield gap between national yield and yield potential. In 2016, Bangladesh imported around 12% of its net cereal demand. The major crops produced in Bangladesh includes rice, maize, wheat, pulses, sugar cane, jute as a major cash crop, vegetables, oil seeds, spice and condiments. The country experiences a lot of environmental variations, six seasons in a year, where the cropping pattern is dependent on seasons. The frequency

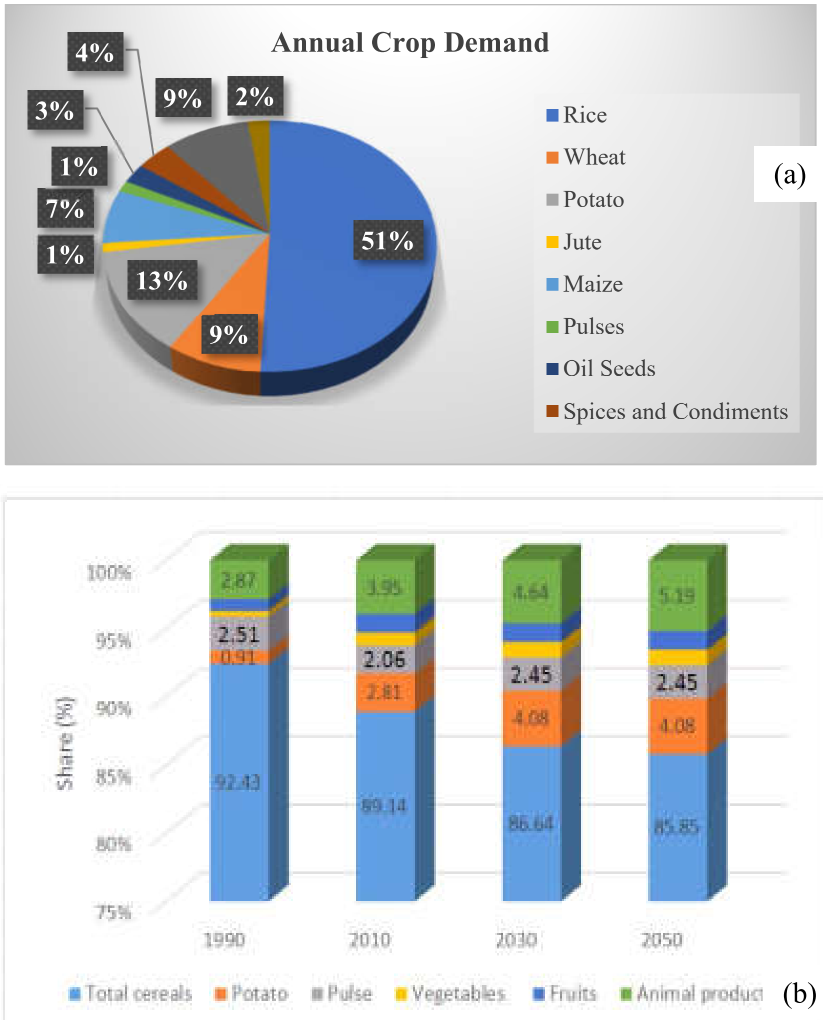

Figure 4:(a) Food production by share in Bangladesh 2016 adopted from BBS (n.d.) and (b)Projection in change in share of food calorie intake reprinted from Nasim et al. (2017)

in land use for cropping ranges from single to quadruple. Among the cultivated crops, rice occupies about 75% of total cropped land (FAO, 2013) because of wide adaptability of rice variants in the country shown in fig. 4. Almost 90% of total rice cultivation practices require irrigation (BBS, n.d.) which is mostly ground water dependent. Land used for rice cultivation can also be used for vegetables, pulses or other seasonal crop production.

Wheat is cultivated during winter, which covers only 5.23% of total cropped land. Maize is cultivated in two seasons and have higher yield than rice and wheat. Maize is well suited crop for charlands (sandy islands) in the country and covers nearly 3.9% of net cropped land. Pulse and oil seed cultivation are also well suited to country's ecosystem. Pulses and oilseeds have both winter and monsoon harvesting variants covers nearly 10% of cropping area. But, the lands for such production are not evenly distributed throughout the country. Sugarcane is cultivated in areas where rice cultivation is difficult, covering 1.25% of arable land. The major cash crop of the country, jute, takes around 8.05% of the total cropped land. Vegetables and spices are well suited crop for winter and produced all over the country including peri urban areas. In 2016, the net cropped area for agricultural production was 7840 mega hectares, which is nearly 60% of total land area of the country. Growing cities and infrastructure development have stressed the pressure on land for agriculture. Bangladesh is also one of the most vulnerable countries to sea level rise which can flood up to 20% of the net cropped land in the country. The southern west part of country is shifting towards shrimp fisheries from agriculture. Food sector is the major water consuming sector in the country. The water productivity (kg/m^3) for major crops are lower compared to other south east Asian countries. On the other hand, food producers in Bangladesh uses nearly double amount of fertilizers and pesticides than recommended amount for crop production. Whereas, the average manual labor and organic fertilizer input for major crop production are comparatively higher. The use of energy in agricultural production takes around 3% of total primary energy use and fertilizer industries takes up to 7%. 90% of total energy required in agricultural production is met by petroleum whereas

10% comes from electricity (IEA 2018). With the improvement of people's living standard, the change in food pattern and demand for protein-based product will increase. Several researches had showed how the consumption pattern might vary in future along with variation in quantity. Islam and Talukdar (2017), used ARIMA model to project diversification in food consumption over time and compared it with domestic production of different crops and protein-based food. According to their projection, rice will be a major part of the calorie intake with a decreasing trend. The volume of production is strongly related with land, water and energy input in cereal production and increased yield in crop production will demand more resource flow in agriculture. The ministry of agriculture of Bangladesh has declared its goal in achieving 100% self-sufficiency in food production, but feeding increasing population along with limited arable land, water resources will challenge the safety balance between food production and import in Bangladesh. The following fig. 4(a) shows food production by share in Bangladesh which also illustrates 4(b) Islam and Talukder's projection in change in future food calorie intake per capita.

2.3 Understanding the Interlinkage among SDG Targets

At the inception of SDG interlinkage realization, multi perspective method for nexus development has been considered which includes analytical method, government tool and emerging disciplines (Keskinen et al., 2016). Blanc (2015) in DESA working paper showed how SDG goals are connected to each other because of core and specific targets of each goal. Fig 5 shows how targets associated to water, connected to SDG 6, food, connected to SDG 2 and energy, connected to SDG 7 expands their influence across the integrated SDG network and associated targets. The subnetwork of water energy and food is directly or indirectly connected to almost all the SDGs. Although, Blanc pointed out that the most influential goal among SDGs is sustainable consumption and production, this goal is explicitly asking for efficient use of water, energy and food for any consumption or production activities. He also pointed out two important issue, economic infrastructure development drives the energy requirements which is also affected by the limiting constraints of CO_2 emission, air and water pollution. On the other hand, goal 13, related to climate change, goal 14, related to ocean and goal 15, connected to ecosystem on land, are more connected to overall environment of the world.

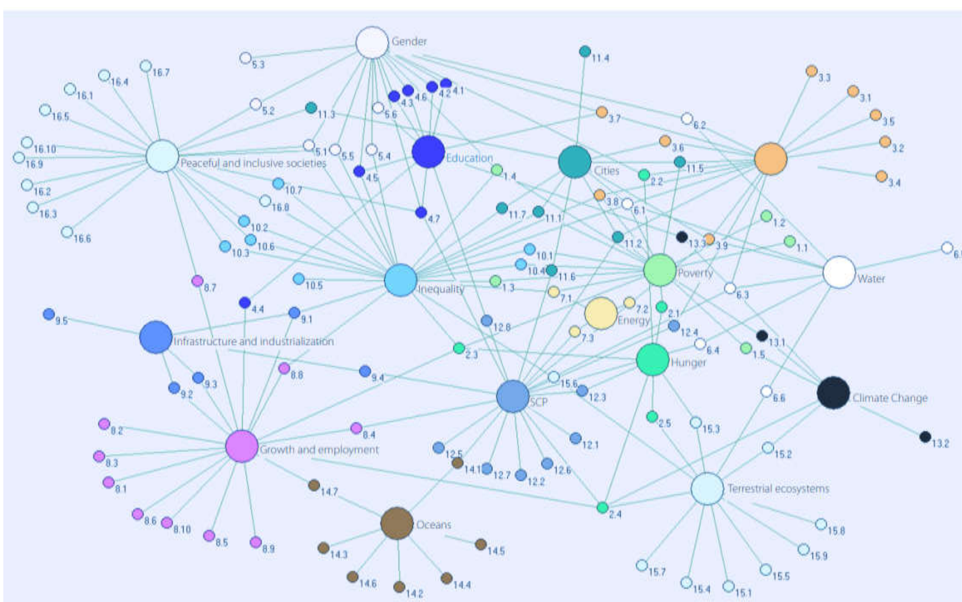

Figure 5: The SDGs as a network of interconnected targets reprinted from Le Blanc (2015)

However, Institute of Global Environmental Strategies (IGES) research report published a comprehensive report on SDG targets of different countries. The report was based on the time series data analysis from 2001-2014, showing the correlation of specific indicator, associated to SDG target, with respect to other indicators. The report considered 51 indicators across 108 SDG targets and produced a correlation matrix based on data found for each country. These data have showed strong correlations among different targets, which provides a starting point to look for causal relationship among targets. Where Blanc tried to stress the interconnections among different SDG targets qualitatively, IGES report showed how each indicator corresponding to specific SDG target is changing. As the resource and welfare management is largely controlled by policies developed and executed by Government, mapping of national policies can help us realize how policies themselves interacting with one another (Nilsson et al., 2016).

2.4 Transcending the Theme of SDG Target Interlinkage to National Priorities of Bangladesh and Policies

Bangladesh has been praised by the United Nations as well as the international development partners as the model for socio-economic gains achieved under the Millennium Development Goals (MDGs). This provides an indication that Bangladesh is well positioned to emerge as a global thought leader with regard to attaining SDG targets as well. Most success in attaining the SDGs will rest, in part, on how well efforts can be guided and where resources are directed. To ensure Sustainable Development Goals in Bangladesh by leaving no one behind in most possible short time, a set of 39 indicators

Table 1: NPIs and SDG targets in comparison

SDG Targets	NPI (By year 2030)	NPIs (by year)
2.2 – By 2030, end all form of malnutrition **2.4**- Proportion of agricultural area under productive and sustainable agriculture	**NPI 3** Reduce the prevalence of stunting among children under 5 years of age to 12% (nutrition based) **NPI 4** Ensure the proportion of cultivable land at a minimum of 55% of the total land area (agriculture)	14.1% (2014) 70.6% (2016)
6.1 - Ensure 100% population using safely managed drinking water services **6.2** - Ensure 100% population using safely managed sanitation services	**NPI 17** Ensure 100% population using safely managed drinking water services **NPI 18** Ensure 100% population using safely managed sanitation services	87% (2015) 61% (2015)
7.1 - Ensure access to electricity for 100% population **7.2** - Increase renewable energy share in total final energy consumption to 10%	**NPI 19** Ensure access to electricity for 100% population **NPI 20** Increase renewable energy share in total final energy consumption to 10%	76% (2015) 3% (2016)
8.1 - Promote sustained, inclusive and sustainable economic growth, full and productive employment and decent work for all	**NPI 21** Increase annual growth rate of GDP to 10%	8% (2019)
9.2 - Raise industrial share of employment and GDP	**NPI 25** Raise industry value added as a proportion of GDP to 35%	21.01%(2016)
12- Ensure sustainable consumption and production patterns	**NPI 31** Ensure 100% installation and operation of waste management system in all industries	60% (2015)
15.1 – By 2020, ensure the conservation and restoration and sustainable us of wetland, forests **15.2** – By 2020, promote the implementation of sustainable management of forests.	**NPI 34** Enhance forest area as a proportion of total land area to 18% **NPI 35** Increase the area of tree-covered land by 25% in relation to the total land area	13.22% (2015) 22% (2016)

has been selected under the instructions of SDG Working Committee of The Prime Minister's Office (BBS, n.d.). Under these indicators, some of the indicators are selected from the global Sustainable Development Goals and some of the indicators are selected after modification on Bangladesh perspective. All relevant ministries are connected with this process (BBS, n.d.). Table 1 shows which national priority corresponding to specific SDG targets and what to be achieved by 2030 (BBS, n.d.). Here, national priority (NPI) 3 and 4 correspond to food, NPI 17 and 18 correspond to water and NPI 19 and 20 correspond to energy. The table also includes economic endeavor of the country through NPI 21 and 25, ensuring sustainable consumption through NPI 31, and use of lands through NPI 4, 34 and 35. If these NPIs are analyzed, it will be seen that NPI 4, 34 and 35 have an inherent competition on land for food production and bio-diversity preservation. Moreover, according to the national industry policy, the country favors agro-based, textile and leather-based industries which are highly water intensive, whereas the water share for agriculture is the highest (FAO, 2008). On the other hand, national agriculture policy is mostly production focused whereas national water policy urges all sector to be efficient of using water resource. Thus, just into the surface of national priorities, it can be seen that there is an uninformed competition of policies towards achieving individual priorities rather than connective initiative. For a country which seeks economic solvency as quick as possible, the prevailing policies developed in silos will always focus on economic growth and promoting elements which are beneficial to economic growth (Liodakis, 2010). In Bangladesh, the WEF nexus approach evaluation was reflected only in a handful of publication in which the prevailing condition in water and agricultural sectors were discussed (Gain et al., 2016; Hussain H. and Ali S., 2017). No studies were done on how two most important long-term planning namely Delta Plan Bangladesh 2100 and Power System Master Plan 2016 will interact with each other or relevant policies were supportive enough to accomplish both national priorities and sustainable development goals. IGES Report 2017 showed the causal relationship between pair of targets to indicate how strong the links are, and ranked the top central SDG targets of SDG network. The report showed agricultural productivity, water security, energy and sustainable consumption pattern are most influential targets. Fig. 6 intends to connect the national priorities with SDG targets and concerned policies to demonstrate a possible interaction among national policies with respect to correlation data which were published in IGES (2017). Here, discontinuous line indicates negative interactions.

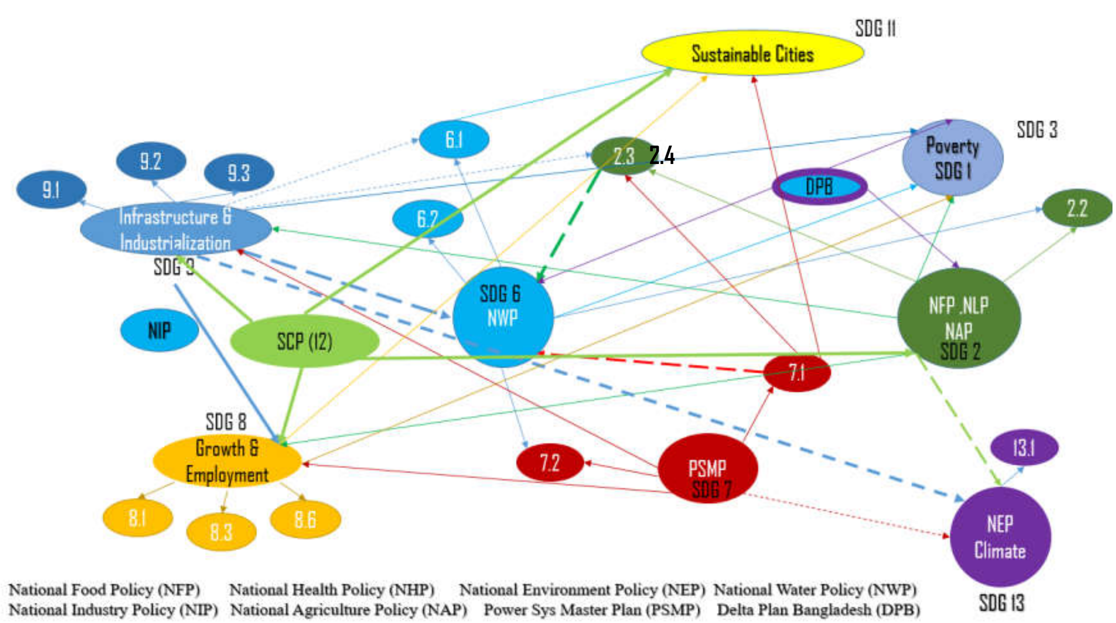

Figure 6: A thematic policy network of Bangladesh contrasted with NPIs and SDGs produced from author's perspective.

2.5 Moving Forward: What Is Next

To author's knowledge, no specific guidelines on how the findings of interlinkage analysis can be used to abridge policy gaps developed in silos and increase interlinkage. If the network of public policies and the prevailing resource management can be overlapped; the contest, synergies, gaps and recommendation on resource management in terms of WEF nexus can help us to build effective policy coherence for sustainable economic, social and bio-physical development within or between geophysical boundaries. Nilsson et al. (2016), had showed the first qualitative approach to screen policies against each other to find out how policies are working for or against each other. A 7-point scaling system was proposed based on directionality, reversibility, strength and certainty of interaction. Zelinka and Amadei (2017) used the basic idea of Nilsson et al. to form a matrix to show how, in a set of individual targets, which targets are more influential to other and proposed a cross impact analysis, which is essentially both qualitative and quantitative approach. This approach is similar to mixed method analysis, extensively followed in public health research arena (Ebenso et al., 2017). The mixed method analysis sets the framework through context setting, development of mechanisms to find out the impact of context on a system and evaluate the outcome. According to Zelinka and Amadei (2017), the cross-impact analysis can provide a quantitative approach on how policies of a country are interacting with each other and what are comparative positions of policies which governs the resources. However, it does not necessarily reflect whether such interactions in policies are causing resource stress as different stakeholders governs resources at different scales. This requires a quantitative platform of resource systems, which can communicate quantitative findings to different stakeholders as they take decisions in future. The framework of **7 Question Guideline(7QG)**, developed by Daher et al. (2017) is one of the robust ways in modelling a resource network based on local characteristics to address policy interactions in the holistic interaction of resource network, i.e. water-energy-food related issues. The guideline provides a perspective view of how to develop a quantitative model that facilitates policy issues or 'modelling nexus issues' based on the cross sectoral interaction of resources by asking set of questions. The guideline starts with identifying critical issues, i.e. *the first question*, whether it is food, water or energy security or the environment to set the perspective view of system of the systems that is needed to be studied. *The second question* focuses on the stakeholders' association and interaction with the system. The feasibility of a solution to address the critical issue, is highly dependent on stakeholders' adaptability and efficiency. The scale of the system in consideration is *the third question*. As the scale grows, the complexity and data requirement for development of the system, grow with it. As mentioned earlier, the system definition comes with identifying critical issues that are needed to be addressed. *The fourth question* deals with development of the system of the systems based on their interactions. The spread of the system should be large enough to capture stakeholders' specific interests connected to the critical issues. The system should be able to capture all the key interactions in the simplest ways. The interactions might vary based on local characteristics and scale. To set a comparative platform, for stakeholders' interests framed as scenarios, *the fifth question* asks to set outputs for the analysis of a given scenario to the defined system. For instance, the Qatar study documented by Daher et al. (2017)

showed how much excess resources does Qatar need to attain food self-sufficiency for different crops. The complexity of the defined system is also related to the data availability. Thus, *the sixth question* deals with the data requirement for defined system. The focus of the data requirement might vary based on priority on interactions, scale and time.

The final question retraces the assessments to the stakeholders. As the model and assessment platform has been developed, the analysis can point out the synergies and trade-offs associated with a particular decision taken by stakeholders. This facilitates stakeholders to take an informed decision based on the interactions of resources in the defined system. For developing a tool that reflects the defined system of the resource subsystems, the framework and methodology of WEF nexus tool 2.0 provides a better understanding of comparative planning strategies of the stakeholders (Daher and Mohtar 2015). Such framework is efficient in projecting different scenarios and provides a comparative platform for a set of strategies to be inspected. It is highly unlikely that all scenarios might be favorable. Moreover, a favorable scenario might not be a feasible one to the stakeholders. Each scenario has its own intervention and how the intervention interacts with resource hotspots as well as who are to intervene should be considered. Thus, the decision dimension also encompasses interests of stakeholders. Daher et al. (2018) proposed a three-filter platform to address the multiplayer, multilayer and multidimensional interconnectedness for screening scenarios. Bio-physical resource limit, government and social players across water, energy and resource subsystems have differing modes of interaction, preference and decision-making power. Daher et al. (2018) described a socio-techno-economic-political perspective, STEP, a three-filter framework, which is an extended and more elaborated scenario inspection framework from 7 question guideline of Daher et al (2017). The framework checks whether a proposed scenario, as a nexus solution addresses specific critical questions.

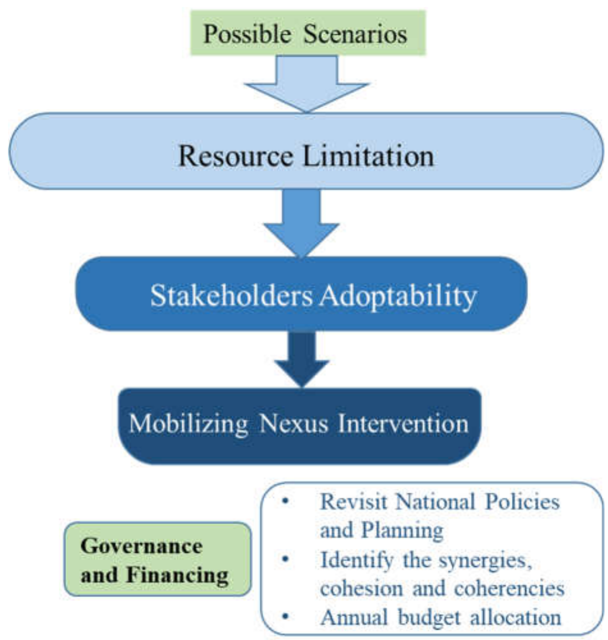

Figure 7: S-T-E-P framework adopted from Daher et al., (2018).

The first filter checks whether execution of scenarios against physical resource constrains at national scale. To put it on plain words, whether a scenario requires more resources than available, such as land, water or more energy. For example, the future energy portfolio under 100% self-sufficiency of food and prevailing water consumption pattern (79% ground water, 21% surface water) under business as usual case for Bangladesh might not be possible because of the physical resource constraints of groundwater. The filter might also consider scenarios favorable to national priorities. This type of filter might be characterized as country specific priority filter based on resource limit and priorities.

The second filter is strongly connected to stakeholders' dynamics and trade-offs. This filter probes for the level of connectedness of stakeholders to scenarios. To elaborate such concept, a decision on limiting ground water use from the government will affect the traditional agricultural practices in Bangladesh. Almost 90% of total cropped land are irrigated, largely by withdrawing ground water. Without making surface water available, as a replace for groundwater, such decision can make crop producers shift towards different crop which has low yield, which can trigger food import or high yield but low in demand in the national food market. On the other hand, withdrawing surface water from waterbodies might negatively affect local fish production and fishermen community. Thus, implementing a scenario in alleviating ground water stress might affect the aggregate crop production and transmit burden to other community. If a proposed scenario, passed through the previous filter becomes infeasible to the second filter question, then the scenario is screened out. The proposed STEP 3 filter framework for scenario selection is shown in fig. 7.

3. HYPOTHESIS

The hypothesis of this study is – "*Adopting a Water-Energy-Food nexus approach to national priority planning of Bangladesh will reduce the stress on core resource requirements while providing the same predicted developments by 2030 and 2041***.**"

In the literature review, it has been shown that WEF nexus approximation has to be screened through the policies existing within a geophysical boundary to realize the implementation constraints of a WEF nexus recommendation. The current policy of Bangladesh is solely focused on economic development and energy solvency is one of the predominant issues that is being discussed in national planning. Several publications have also showed that living quality of human is directly linked to economic development (Wayan et al., 2019). Moreover, many research publications both national and abroad, suggested the economic development nexus is directly linked to consumption of energy (Alam et al., 2012; Sarker, and Alam, 2010; and Khan et al., 2016). In all of these publications, neither the environmental impact and cost, nor the type of energy usage (domestic or industrial) were considered. The existing policies seem to favor water thirsty agricultural and industrial practices which has been fueled by secondary for of energy availability. On the other hand, the choice of primary energy source has more impact than secondary for of energy because it includes the impact of conversion on environment. Any policy gap can constitute uncertainty, which can result in a threat or risk. Bangladesh has formulated two long term planning, Delta Plan 2100 and Power System Master Plan 2016. These two major development plans are not directly connected because of two major reason. The energy sector of Bangladesh is slightly import oriented, oil and LNG being imported from abroad, domestic coal production is limited whereas the only domestic energy source is natural gas which is also depleting unless new reservoirs are discovered. Moreover, there is unavailability of opportunity for hydropower in Bangladesh (PSMP, 2016). On the other hand, the Delta Plan is mostly water, land and food oriented. Thus, two planning are exclusive when it came to realizing the direct impacts on planning decision made in both planning. However, the indirect relationship, interdependencies and trade-offs

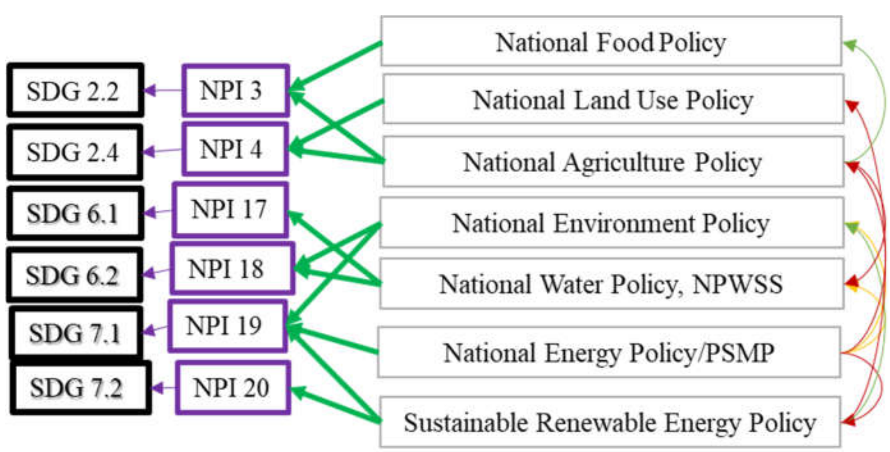

Figure 8: Interconnection and constraints among national policies, priorities and SDGs.

will be conspicuous if all the related policies connected to these two master plans. It is important to state that, these national policies are also aiming to achieve national priority goals relevant with sustainable development goals. The following figure shows how different policies and priorities are boosting or constraining with each other while trying to achieve individual goals (Fig. 8). The current policy coherency is seen most in water-environment and water-food nexus. The national water policy 2018 has only connected water to energy when it came to hydro-electricity (Gain et al., 2018). Whereas, the agriculture and industry policy mandates availability of water from any source regardless of water use efficiency.

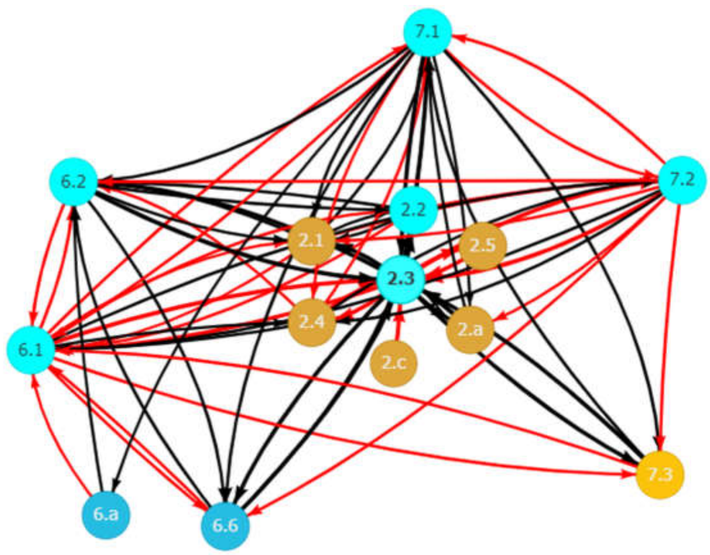

Figure 9: Interlinkage among targets of goal 2, 6 and 7. The black line indicates positive linkage and red line indicates the negative linkage across targets generated from open source SDG interlinkage tool.

However, water policy is more preservation oriented but water use efficiency has not been clearly presented. The energy policy is more concentrated on energy solvency and national environment policy has also provided regulation for limiting the pollution, but the PSMP 2016 is promoting water thirsty and pollution prone energy choices, thus the planning and policies are seeming losing coherency. According to IGES report (2017) and with the aid of SDG linkage visualization tool, the competition among SDG targets associated with goal 2, 6 and 7 is depicted in fig. 5. This figure also indicates the trade-offs and synergies among targets which are not associated with national priorities. In both cases, policy mapping and WEF nexus with respect to SDG generated from SDG interlinkage tool, it can be seen that the competition among policies are quite similar to fig. 9. In addition, the network depicted in figure above also shows how other goals, which were not considered in national priorities are competing with each other. Thus, this provides a conceptual evidence for the hypothesis which will be tested through building WEF nexus analytics of Bangladesh at national level.

4. RESEARCH METHODOLOGY

The methodology for this study is designed to find out the ways to attain the objectives in **four phases**. At the **first phase,** interaction among policies with respect to national priorities, connected to water, energy and food, are intended to be identified, scaled and put through a conceptual cross impact analysis to point out the critical, influential and dependent issues. In the **second phase**, the interconnected resource subsystems; the system of the systems is being identified, based on the cross sectoral interconnections of the core resource network; water, energy, food and the peripheral network; land and emission in the environment. A resource balance sheet for water, energy and food are to be prepared for base year which is 2016, identifying the national capacity for bio-physical resources and the local characteristics of cross sectoral resource flow. Then, based on the national projected food, energy and water demand, published in national priority planning, a resource balance in future timelines, 2030 and 2041 is produced to qualitatively identify resource hotspots and probe whether the policy interaction, conceptually identified in phase 1, reflects or recognizes these cross sectoral hotspots. In the rest of the phases, the **7-Question guideline**, developed by Daher et al. (2017), is used to guide the development of the WEF nexus analytics for the study. **Phase 3** includes the identification of the critical question of the study, a computational framework of the WEF network model at national scale for Bangladesh is being developed, for the system of the systems identified in phase 2. The computational framework is being used as a tool, for assessing different scenarios, reflecting priorities for each of the policies considered in phase 1 (Daher and Mohtar, 2015). Stakeholders, as per their individual role and involvement with each of the resources, policies and national priorities are being identified. The assessment parameters are being set for providing a comparative platform for different scenarios. Then, assessments for each of the scenarios are being converted as indicators defined by national priorities, sustainable development goal targets and holistic resource demand to probe whether any scenario exceeds the bio-physical resource limit. In the final phase, **phase 4**, assessments for each scenario will be compared against each other, in terms of indicators of national priorities and assessments, to find out for which set of scenarios, the projected outcomes attain national priorities, SDG targets with reduced pressure on resources and how does it involves the stakeholders identified in phase 3. The conceptual flow diagram of the method followed in each phase is shown in fig. 10. Phases are further discussed as follows:

Phase 1: *Mapping national policies and planning to SDG and NPI targets*

a) Connect existing policies for water, energy and food production in terms of SDG target and national priorities.
b) Develop a conceptual map, connecting each of the policies, in terms of interaction across identified policies.
c) Assessment of identified interactions through cross impact analysis described by Zelinka and Amadei (2017) and Nilsson et al. 2016. This type of calculation is highly intuitive, but offers a better starting point for evaluating policy interconnections and understanding cohesions.

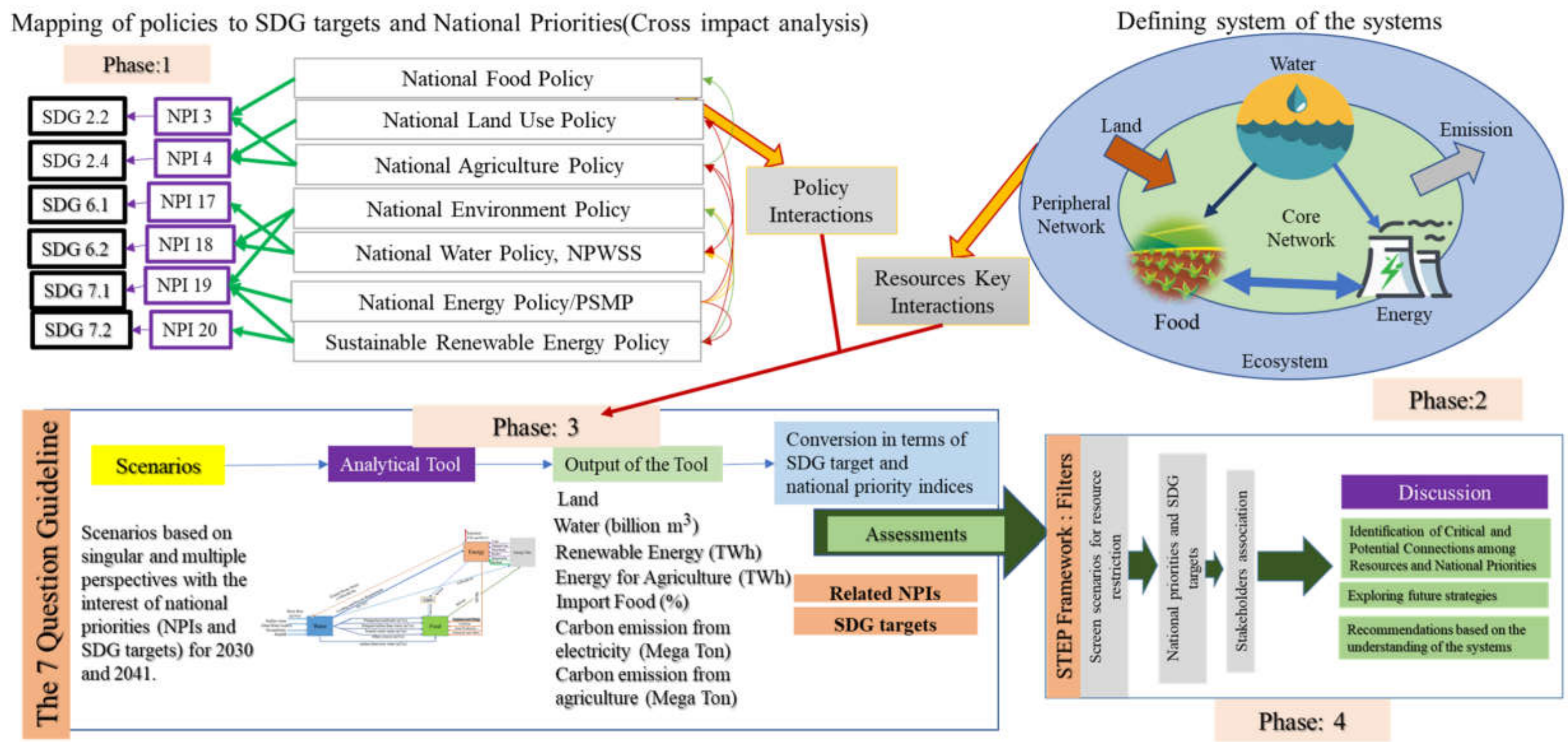

Figure 10: Proposed process flow diagram for the methodology. The arrows indication the path of process flow, where the number indicates the order of processes.

Phase 2: *Interaction of resource subsystems based on resource flow, national priorities and identification of the resource hotspots*

a) Identify individual resource subsystems based local characteristics; define the core resource interactions and peripheral interactions as well as the system of the systems that will be looked into.

b) Document the bio-physical resource balance for Bangladesh. Based on documents published by concerned ministries and research groups, the implied resource demand due to future demand, in 2030 and 2041, possible resource hotspots will be identified.

c) Based on cross impact analysis, to be made in phase 1, the interaction among policies will be mapped against resources, as predicted to be critical, due to future demand. This provides an indication whether policies, developed in silos, acknowledging or neglecting the resource hotspots.

Phase 3: *Development of a tool that captures the model, data collection, development of scenarios, set assessment parameters to translate scenarios in terms of national priorities and SDG targets following the 7-Question Guideline.*

a) Transfer model understanding, described in phase 2, into a computational tool, input and output are being defined and set for assessment.

b) Collect data, estimating resource flows and testing the tool with base year (2016) data to realize how much the tool can capture compared to real data.

c) Identify stakeholders, the government institutions, tightly connected to described policies, mapped in phase and discuss their roles, priorities and goals.

d) Develop base scenario based on the future planning of each of the ministries (stakeholders).

	100% Domestic Prod Top ten crops	95% Domestic Prod 5% Import	90% Domestic Prod 10% Import	85% Domestic Prod 15% Import
Scenarios	Coal 60% Gas 10% Renewable 0% (Solar) Oil 15% Import 5%	Coal 45% Gas 25% Renewable 0% Oil 15% Import 5%	Coal 35% Gas 35% Renewable 5% Oil 15% Import 10%	Coal 30% Gas 25% Renewable 10% Oil 10% Import 10% Nuclear 15%
Surface Water 30% Groundwater 70% TWW 0%				
Surface Water 40% Groundwater 60% TWW 0%				
Surface Water 45% Groundwater 50% TWW 5%				

Figure 11: A representation on development of scenarios through selection of a set of interventions.

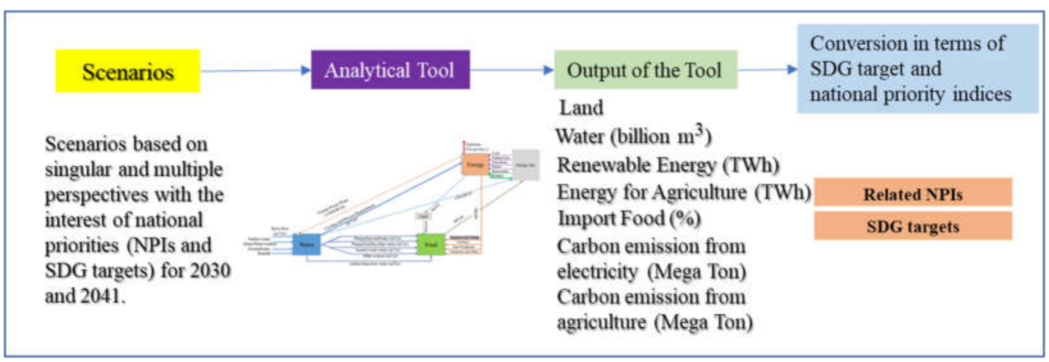

Figure 12: Proposed computational framework of the tool.

A set of scenarios are also developed, addressing resource hotspots, stakeholders' priorities and assessments are compared in a common platform. Fig. 11 shows the conceptual matrix for development of scenarios based on selecting a set of interventions. Suitable user interface and Microsoft excel are used for developing dynamic feedback models. Fig. 12 captures the proposed scenario base computational framework.

Phase 4: *Transcending assessments and findings as policy recommendation*

a) Assessments for each of the developed scenarios are revisited to identify the critical conditions as well as potential conditions, that comes with each scenario. The stakeholders' involvement and interests are being screened to find out feasible solutions. In this case, STEP framework is being used (Daher et al., 2018).
b) The features of silo and multi perspective scenarios are being discussed.
c) How to inform the potential and critical interaction of resources to stakeholders are further discussed along with some recommendations (in the discussion).

4.1 Quantitative and Qualitative Analysis of the Related Policies

4.1.1 National Priorities, SDG Targets and Corresponding Policy Mapping

To assess the level of interaction and influence among policies corresponding to each NPIs, this study proposes the quantitative cross impact analysis described by Zelinka

Table 2: Identifying the interconnection among national policies, NPIs and SDG targets

National Policies/Plan/Strategies			National Priority Index (with indicator)	SDG Targets by 2030
Aligned	Against	Reasons		
National Nutrition Policy 2014 National Food Policy 2006	-	-	3 - Reduce Stunning <12%	2.2 End all form of malnutrition

Table 2: Continued

National Policies/Plan/Strategies			National Priority Index (with indicator)	SDG Targets by 2030
Aligned	Aligned	Aligned		
National Agriculture Policy 2013	National Water Policy '18	Current agricultural practice is heavily groundwater dependent (79%), increased productivity requires increased irrigation, NWPo discourages intensive use of groundwater (para 4.3, 4.6)	4 - Proportion of cultivable land by at least 55%	2.3 Double agricultural productivity and incomes of small-scale producers, family farmers, pastoralists and fishermen, including thorough secure and equal access to land.
	Power System Master Plan '16	Increased use of coal-based power generation plants will affect water, soil and air quality, thus limiting countrywide crop intensity.		
National Land Use Policy	National Industry Policy '16	Establishment of economic zone in government owned land and alluvial island thus limiting agricultural activities (para 6.1)		
National Water Policy 2018 National Policy for Safe Water Supply and Sanitation 1998	National Agriculture Policy; National Agriculture Extension Policy	Crop intensification (Para 3) -increased use of fertilizers, manure and pesticides affecting the quality of water. Use of groundwater resulting lowering of groundwater level and contamination of rear earth metal contamination	17 - 100% safely managed drinking water	6.1 Achieve universal access to safe and affordable drinking water.
	National Industry Policy' 16	Absence of limitation on extracting groundwater, prioritizing industrial growth. (Para 3.3.18)		
	PSMP 2016	Increased use of coal in electricity.		

Table: Continued

National Policies/Plan/Strategies			National Priority Index (with indicator) Aligned	SDG Targets by 2030 Aligned
Aligned	Aligned	Aligned		
National Policy for Safe Water Supply and Sanitation 1998	-	-	18 – 100% safely managed sanitation services	6.2 Achieve access to adequate and equitable sanitation and hygiene for all.
National Energy Policy Power System Master Plan	National Environment Policy	Using coal for power generation is polluting, discouraged to use low grade coal	19 - Ensure access to electricity for 100% population	7.1 Ensure universal access to affordable, reliable and modern energy services.
	National Land Use Policy	More establishment of powerplants require more land.		
	National Water Policy	Thermal power plants require fresh water for cooling and operation. The water use efficiency is absent.		
PSMP 2016 DP 2100 SREDA 2012	National Land Use Policy	Establishing solar park and wind-based power plant requires land.	20- Increase renewable energy share in 10%	7.2 Increase renewable energy share by to 10%

and Amadei (2017) coupled with qualitative policy interaction scaling approach of Nilsson et al. 2016. Nilsson and his colleagues proposed a simple rubric method for practical policy makers to identify negative and positive interactions under seven-point scaling method. The scaling method was developed on four consideration; directionality, reversibility, strength and certainty of interaction. It was emphasized that the negative or positive interaction may come from legal or government procedure. This type of calculation is highly intuitive, but offers a better starting point for evaluating policy interconnections. On the other hand, Zelinka and Amadei (2017), expended the idea as they scored the interconnection of each SDG to other, put them all in a matrix to see how on specific SDG has influence and dependent on other goals through cross impact analysis, a general method to screen the strength of factors among a set of interacting factors. In order to do the similar analysis, nine national policy and two long term priority planning has been mapped to identify how the policies are interconnected to attain the national priority goals and SDGs. The following table shows how the national policies are interacting with each other with individual commitment to national goals which is simple *a qualitative approach*.

4.1.2 Cross Impact Analysis Among Priorities and Targets in Perspective of Interacting Policies

As the table shows the interaction among policies towards a specific national priority, it does not necessarily indicate the degree of interaction. The interactions are required to be assessed in terms of strength, directionality and certainty. To address this issue, the proposed method of Nilsson et al. 2016 has been adopted in evaluation of certain interaction. Whereas they illustrated a 7-scale interaction (From -3 to +3), this estimation adopts a 5-scale interaction (from -2 to +2) among goals and targets, to individual policies or to actions. The interaction was mapped based on SDG 2, 6 and 7 to translate the impact of pollution on WEF nexus. The positive interaction implies building strategies across sectors for preservation and management (Nilsson et al., 2016). Negative interaction suggests trade-offs, opposing impacts, scopes for risk where government/stakeholders need to put more attention to needle up interaction among resources (Nilsson et al., 2016). There are four main considerations when applying the scale.

1. Reversibility of interaction. Such as using more land for building water reservoir (SDG 6.1) can put pressure on farmland (SDG 2.4) and vice versa.
2. Directionality – Does energy consumption ensures water quality or water quality can affect energy consumption.
3. Strength- Does renewable energy production put significant stress on agricultural land or contributes weakly for preserving the environment.
4. Certainty- Can more food production ensure effective reduction of malnutrition or else.

Essential assumptions which have been made for scaling-

1. The scaling system is not based on status-quo, it is based on how existing policies governing resources and practices will act with each other if a goal is achieved;
2. All of the policy interactions were seen based on recent updates. Scoring scales+2=reinforcing, +1=enabling, 0=consistent, -1=constraining, -2=counteracting.

Table 3: Interaction of policies to attain NPIs and SDG targets

NPI s and SDG Targets	**Resource**	**Policy working towards or against the goal and how**	**Level of Interaction**	**Competing NPI or SDG**	**Resource**	**Aiding NPI or SDG**	**Score**
NPI 3 SDG 2.2	Food	NNP, NFP	Interacts positively, reinforcing	-			-

Table 3: Continued

NPI s and SDG Targets	Resource	Policy working towards or against the goal and how	Level of Interaction	Competing NPI or SDG	Resource	Aiding NPI or SDG	Score
NPI 4 SDG 2.4	Land for food	NLUP National Agriculture Policy Preserve agricultural land for food production	Interact Positively Reinforcing			-	
		NWPo Limiting ground water use for irrigation, urging for water efficiency	Constraining	SDG 6.1, 6.4 NPI 17	Fresh water		-1
		NNP, NFP	Enabling	NPI 3	Food		+1
		PSMP 2016 Depending on fossil fuel, Increased dependence on coal, pollution from waste disposal, using land for power plant	Counteracting	SDG 7.1 NPI 19	Clean water, land and air		-1
NPI 17 SDG 6.1	Drinking water	NWPo NPSWSS	Enabling				
		Food and Nutrition	Enabling			NPI 3 SDG 2.2	+1
		National Policy for Safe Water Supply and Sanitation	Reinforcing		Fresh water		+1
		NAP Crop intensification through irrigation, using fertilizer (inorganic), using groundwater for irrigation lowering groundwater level, arsenic pollution	Constraining	NPI 4 SDG 2.4	Fresh water (ground water)		-1

Table 3: Continued

NPI s and SDG Targets	Resource	Policy working towards or against the goal and how	Level of Interaction	Competing NPI or SDG	Resource	Aiding NPI or SDG	Score
		PSMP 2016 Using water for thermal cooling of the power plant Disposing waste water in the river (irreversible damage) SREDA (Hydropower)	Constraining	NPI 19 SDG 7.1	Fresh water		-1
NPI 18 SDG 6.2	Safe water	NPSWSS Food and Nutrition PSMP Increasing energy supply for growth	Reinforcing Enabling Interacting Negatively/ Constraining	-	-	NPI 17 NPI 3 NPI 19 SDG 7.1	+1 +1 -1
NPI 19 SDG 7.1	Energy	PSMP Increasing energy supply for growth NEP Using environment friendly fuel, setting standard for waste disposal and emission NWPo Promoting Hydro-electric power plant, water recycling plant, preserving water quality, water demand for thermal cooling NAP Energy for agriculture and agro-based industries.	Interacting Positively Counteracting Enabling Counteracting Enabling	- SDG 6.1, NPI 7.1	 Fresh water Air Energy Fresh water Food	NPI SDG 6.1 SDG 6.1, 6.2	- -1 +1 -2 +1

Table 3: Continued

NPI s and SDG Targets	**Resource**	**Policy working towards or against the goal and how**	**Level of Interaction**	**Competing NPI or SDG**	**Resource**	**Aiding NPI or SDG**	**Score**
NPI 20 SDG 7.2	Energy	SREDA 2016	Interacting Positively	-			-
		NLUP Stress on land use for establishing solar park, hydroelectric nd wind power-plant	Constraining	NPI 4 SDG 2.4	Land	NPI 19 SDG 7.2	-1
		NEP Promoting cleaner form of energy	Reinforcing				+1

NNP= National Nutrition Policy, NFP= National Food Policy, NAP= National Agriculture Policy, NWPo=National Water Policy, NFLP= National Fisheries and Livestock Policy, NLUP= National Land Use Policy, PSMP=Power System Master Plan, NEP=National Environment Policy, NPSWSS=National Policy for Safe Water Supply and Sanitation, SREDA=Sustainable Renewable Energy Development Authority

The table 3 illustrates how different policies are influenced by and influential on other policies based on assumptions made previously. The analysis shown in table above and below are known as cross-impact analysis, where the influence of on policy connected to particular resource is screened against other policies to find out their dependencies and influences across water energy food networks. The calculations were done using the formula showed by Zelinka and Amadei, (2017) keeping the priority equal across all sectors. Based on the table above, a cross impact analysis for NPIs/SDGs has been tabulated in table 4. Here, the term IR index denotes influence to dependence ratio, which focuses on the efficiency of a goal to elicit change on other goals (Zelinka and Amadei, 2017). The net influence index NI was used to calculate the difference between influence and dependency. Priority Index (PI) = A(weight of influence ratio)*(IR-minIR) / (maxIR

- minIR)+ B(weight of influence)*(NI- minNI)/(maxNI-minNI); This index ranges between 0 and 1 with small values indicating goals with low priority and high values representing high priority goals. The analysis assumed equal weights (A = B = 0.5) for both IR and NI. There could be specific circumstances, however, where the weights are not the same; their sum must always be equal to 1. If decision makers wantsto focus on generating as much impact as possible regardless of efficiency of distributing resources, then they would focus solely on the NI and select B = 1 (A = 0). Conversely, A= 1 (B = 0) would correspond to the most efficient allocation of resources as opposed to absolute impact (Zelinka and Amadei, 2017). The PI values will differ if nexus considers more SDG targets.

Table 4: Cross impact analysis of NPIs based on prevailing policies

NPIs/ SDGs	NPI 3	NPI 4	NPI 17	NPI 18	NPI 19	NPI 20	Influence	Influence Ratio (IR)	Net Influence (NI)	Priority Index (PI)
NPI 3/ SDG 2.2	-	0	0	-	0	0	0	0	-3	0
NPI 4/ SDG 2.4	+1	-	-1	-	-1	0	-1	0	-1	0.17
NPI 17/ SDG 6.1	+1	-1	-	+1	-1	0	0	0	0	0.25
NPI 18/ SDG 6.2	+1	0	+1	-	-1	0	+1	1	0	0.75
NPI 19/ SDG 7.1	0	+1	-1	-	-	0	0	0.2	3	0.55
NPI 20/ SDG 7.2	0	0	+1	-	-1	-	0	0	0	0
Dependent	+3	0	0	+1	-3	0		-	-	

From the cross-impact analysis shown in table 4, it can be seen that under equal weights, high priority sector in WEF nexus is water, followed by energy and food production whereas energy is most influential among these three. From the assessment, it is quite clear that food production is using more resources in resource subsystem. If we consider on an economic point of view, food is a private good, grown by the people, energy is a public good regulated by the government, whereas water is mostly free good in Bangladesh, making its consumption and usage more vulnerable than others.

Table 5: Correlation matrix of SDG adopted from SDG interlinkage visualization tool

NPI	3	4	17	18	19	20
SDG	2.2	2.3	6.1	6.2	7.1	7.2
2.2	0	0	-0.97	0.99	0.99	-0.99
2.4	0	0	0.92	-0.94	-0.94	0.95
6.1	-0.97	-0.95	0	-0.97	-0.97	0.97
6.2	0.99	0.97	-0.97	0	0	0
7.1	0	0.97	-0.97	0.99	0	-1
7.2	0	0.97	0.97	-0.99	-1	0

However, to test the finding from different approach, the correlation matrix based on time series data from year 2001 to 2014, published in IGES report of Bangladesh showed similarity of the aforementioned findings. Three tables were produced to see how the bio-physical resource goals are correlated. The policies discussed here has been kept mostly unchanged over the period of 2001-2014 and can be considered as past case for business as usual process. Table 5 shows how, the resource subsystems are correlated to each other. In both analysis, which were done independently, has shown significant stress on resources for attaining isolated goals. It is important to point out that correlation matrix does not indicate causation but still the negative values of correlation appear in places where cross impact analysis predicted stress and vice versa.

4.2 Interaction of Resource Subsystems Based on Resource Flows, National Priorities and Identification of Possible the Resource Hotspots

In this subsection, the methodology will follow the seven question guildeline (7QG) and STEP framework in testing the hypothesis. The hypothesis is considered as the critical question here. The system definition in terms of scale, scope, necessary data requirement and assessments has been described here followed by the identifying stakeholders and their institutional interaction.

4.2.1 Defining System of the Systems and Scale: Water, Energy and Food Interactions

Water, energy and food interlinked network has been defined from various perspectives, i.e. resource efficiency (Daohan et al., 2020), sustainability (Daher and Mohtar, 2015), economic efficiency and levels, i.e. global, regional, transboundary, national and local. At the national level, modelling mainly focuses on both individual and interconnected resource subsystems, along with nature, ecological and technological interactions (emission by different technological process, waste water generation from cropping, blue water consumption for agriculture and energy, land and additional energy requirement). It is true that there are other actors outside water energy and food network which have positive or negative influence on resource subsystems, realizing core network interactions can help us understanding the impacts, synergies and trade-offs on macro perspective. Once a model been developed for water, energy and food network at a national level, the holistic impact of a policy decision can be simulated through the model and the output can be converted and compared with national priority and SDG target indicators to observe whether a policy has direct or indirect, positive or negative impact on other resource subsystem, pushing resources to physical limit, thus threatening sustainability of resource usage. For the purpose of this study, policies undertaken by different ministries, connected to water, energy and food, will be converted in to the input scenario to WEF model, developed based on local characteristics to quantitatively measure physical resource requirement, the stress on the resources and environmental implications. Thus, the developed model can establish a link between the core network (WEF) and the environment which has

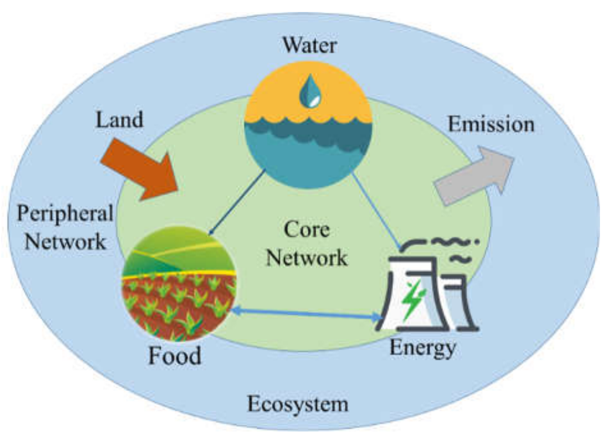

Figure 13: Conceptual framework of WEF interaction for the study.

been shown in a conceptual illustration in fig. 13. In order to develop the core resource network, interactions are developed based on demand and supply value chains, that is what is the demand and how different supply scenarios can quantitatively show different result. For example, in respond to a specific amount of electricity demand, choosing coal or gas or renewable as supply source can show different results in terms of land used, water footprint and Green House Gas (GHG) emission for each of the choices. Thus, interlinkage within core resource network can be characterizes into technical, physical and structural flow (Daohan et al. 2020). The technical flow is similar to input-output flow. For example, treated waste water usage for agriculture might significantly increase the energy intensity and carbon footprint in food production while increasing the water productivity (Karan et al., 2018). This type of flow assessment is a hotspot in WEF nexus research, address trade-offs and synergies among water, energy and food interaction to improve sustainability. The physical flow relates WEF network to biophysical environment. For instance, construction of hydro power plant can reduce water and land availability for food production because of larger foot print of water and land for such plants. Renewable or clean energy resources have higher land footprint compared to traditional energy production, which can stress land requirement for production. The structural flow represents the interaction between WEF consumption behaviors and national practices. For instance, the prevailing ground water dependency in agriculture has a little impact on net water resources of the country compared to ground water. Increasing energy efficiency might led to more energy consumption. Change in pattern in calorie intake per capita can increase the demand of a particular crop which has less water footprint and yield, thus reducing the aggregate domestic production (producing more wheat at expense of rice). The interaction between core resource network and peripheral network, i.e. the environment is included in the model. The model has flexibility in incorporating the impact on resource thresholds based on climate change, which decreases the resource availability. The environment, i.e. natural ecosystem provides land, water and primary energy for national WEF provision and effective disposal of waste (gray/waste water or GHG emission) for human activities (de Grenade et al., 2016). The impact of population growth or change in demand structure of food and the implication of such change are also needed to be simulated by the developed model. For translating a policy implication to such model, the focus should be concentrated in the balance of ecosystem demand, resource threshold and human activity demand in WEF resources. The model has to be flexible in changing the demand, technological, physical and structural flow of resources, impose resource threshold to project any future scenario. Bangladesh has underlined its objectives through long term planning in food and energy sector considering social, economic and environmental dimensions. The country is aiming to attain food self-sufficiency, ensure affordable energy for development and preserve its ecological sustainability through long term planning with massive investment in infrastructure development. Developing a WEF nexus model for Bangladesh should be able to show the resource requirement for each planning to be fulfilled, identify the critical resource and also show implications of alternative scenarios which can establish balance between demand and supply while reducing the pressure on WEF resource network. Such quantitative analysis can be interpreted as a set of policy recommendations. Still, projecting future demand is tough and having flexibility in resource flow due to technological or structural change can make a model more versatile in analyzing the dynamic interactions for any policy decision in future. For this study, the holistic system of food production, energy generation and source specific water usage are being considered. The system under consideration does not have any spatial or temporal specification such as seasonal variability of crops, water availability in wet or dry season, or renewable electricity generation. The system only considers resource flow across resource subsystems and how does an increased demand from on subsystem affects other resources. The core system considers water, energy and food production, as well as other resources supporting or affected by the WEF core network, such as land and air, which is considered as peripheral network interacting with core network. Thus, the system of the systems is strictly confined to inter sectoral interactions for the study.

4.2.2 Resource Balance

Land and water resources are dependent on geography and physical boundary of a country. Dependent resources such as food are also bounded by resource limitation of the limited resources. On the other hand, if any limited resource is already being used to its limit, there is a slim chance for other resource dependent on it, might increase in a higher proportion. In such case, flow of such resource outside the geophysical boundary or import is considered. Import can be as high as demand, but it also requires ample financial support to do so. Thus, there lies a balance between how much resources can be imported while meeting the demand for most of it locally. For a country like Bangladesh, which is blessed with huge amount of environmental water flow, also faces resource limit temporally and spatially, because of extreme dependency for a source which has a limited reserve. In the north west part of the country, agriculture is highly ground water dependent, driving the water level lower by each year. In absence of proper distribution mechanism, not overall, but specific source of a resource system can face limitations. Future food demand is highly dependent on population growth.

Table 6: Resource balance for year 2016

Food Demand (KMT)		Water Balance in BCM		Energy Demand in 2016(MW)	
Rice	36000	Surface	83.91	Coal	200.0
Wheat	6000	Ground	21.09	Oil	4126.0
Potato	9476	River flows	1122	Natural Gas	7529.0
Jute	835	Arable Land 8.6 M ha		Biofuel	0.0
Maize	4900	Land used 7.9 M ha (92%)		Electricity Import	600.0
Pulses	1029	Population Growth	0.8%	Electricity Nuclear	0.0
Oil Seeds	1800	Projected Electricity Demand		Hydro	230.0
Spices	2675	Quantity (MW)	Year	Solar	161.0
Sugar Crops	6487	32000	2030	Wind	2.0
Vegetables	1634	54000	2041		

KMT=Kilo Metric Tonnes, BCM= Billion Cubic Meters, MW= Mega Watt, M ha= Mega Hectare

To understand the resource balance of Bangladesh, the table below (table 6) documents the national food demand for base year 2016, projected population growth, present resource volume of land and water, as well as projected energy demand for Bangladesh. As discussed in previous subsection, policies connected to WEF resources are highly prioritized towards water, influenced by energy and food production. For the time being, the resource balance we have might support the demand, but the way the country is directing its resource flow, it is inevitable that the country might face shortage in supporting its demand by over exhausting resources. For example, agriculture sector uses almost 92% of total arable land for food production (AIS 2018), withdrawing 68.3 billion cubic meter water (Amarsinghe et al. 2014), of which 79% are being withdrawn from ground reserve (Aquastat, 2008), where the volume of water withdrawal is almost 2.5 times higher than the total reserve. If this resource flow keeps going on, soon the grown water reserve will be depleted while keeping other sources of water unutilized. Thus, realizing resource balance and future demand of resource for a country helps us to provide a picture on country's physical constraints of resources. Such information can help decision makers to acknowledge informed choices for shared resource management and future development. From the resource balance, it is conspicuous that land and source specific water reserves will reach their physical limit if the business as usual process, prioritizing water for drinking and sanitation rather than diversifying water resources for food production (which is also a solution for managing safe water), or energy production rather than sustainably manage the land use for food. Thus, the focus of resource hotspot and influential policies are on concentrated on the same point. This urges for development of an informed integrated action via understanding of local resource characteristics and finding out whether there are other alternative solutions out there which might acknowledge these resource hotspots and divert concentration of policies for coherent long-term planning for future.

4.3 Representation of System of the Systems, Data Collection, Stakeholder Identification, Development of Scenarios and Setting Assessment Goals

In understanding the systematic and dynamic relationship among resource subsystems, a computational framework is required to be built which captures the local resource flow to simulate the impact of a future demand or intervention on the core and peripheral resource system. Based on supply, consumption and emission processes of each resource system, that is water, energy and food respectively, the holistic interaction of WEF nexus, i.e. core network and impact on peripheral network can be analyzed. Thus, to model a WEF nexus on national scale, a resource system must be viewed on singular perspective. In this study, resource interactions among major crop production, energy production and water security have been focused, whereas other sectoral interactions such as domestic, industrial or commercial use of the resources and resulted impacts have been skipped. The modelling of single resource perspective of water, energy and food nexus has been framed in terms of interaction among resources and consequence to natural ecosystem. Each relationship will be expressed in simple equation to provide the model a mathematical representation for resource flow. Then, these equations and corresponding units of resource flow will be used to form a quantitative framework for the whole model.

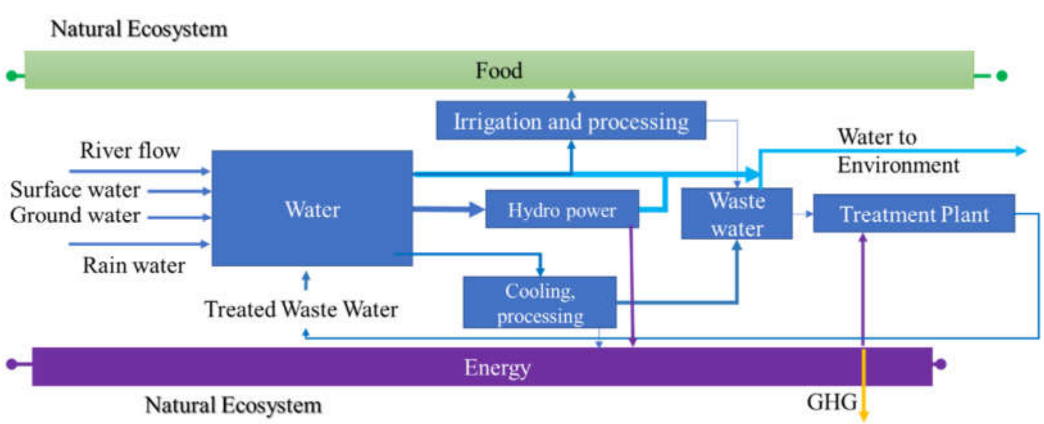

Figure 14: Water centric WEF resource interactions.

The water perspective in WEF resource network is illustrated in fig. 14. Within such network, water system includes irrigation and processing for agriculture, domestic, industrial water use, water for thermal processing and cooling to produce energy and energy input to treat waste water or desalination plant. For the case study, the interaction of water with food production, energy production and conversion has been focused. To define the water sources within such system, the environmental water flow, such as rain water, river flows, along with renewable ground water, surface water and treated waste water sources are taken as resource inflows in the water perspective network. In the water-food interaction, agriculture in Bangladesh is mostly ground and surface water dependent. Treated waste water facilities are mostly located in peri urban areas to supply water in peri urban farm lands (Roy et al 2013).

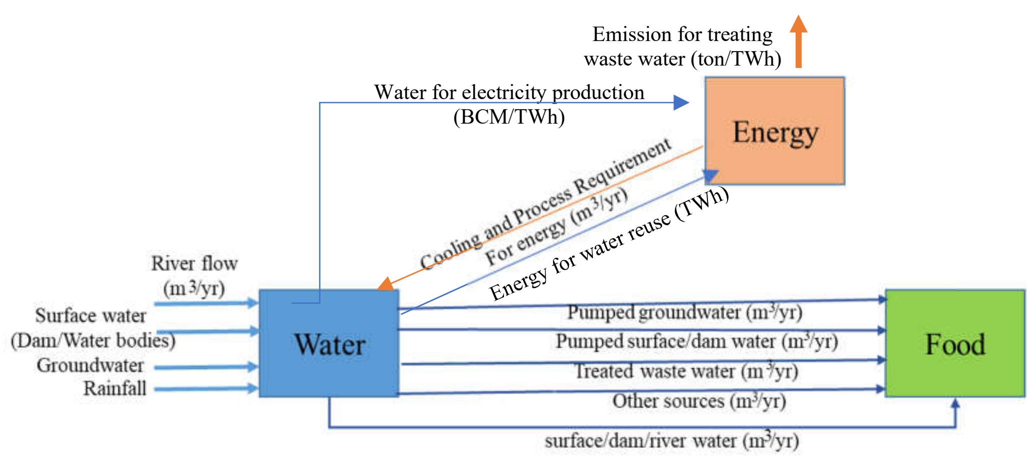

Figure 15: The water resource input and output in WEF network.

Desalination plants are small in scale and used for supplying drinking water in the south western part of the country. Rain water harvesting is also limited to drinking water facilities in rural places. For simplification, it is assumed only waste water treatment technology is responsible for the supply of reusable water. The water consumed during food production, can be modeled by multiplying water productivity for each crop which accounts for the consumptive water use including irrigation and processing. In agriculture, water productivity (kg/m^3) shows how much water is needed for producing different crops, a resource flow of water to food production (Amarasinghe et al. 2014).Mekonnen and Hoekstra had also showed the global water requirement for each crop by sources, namely green, blue and grey water. Based on the resource flow from different water sources and reserve volume, it can be calculated that which water sources in the country is under stressed or overstressed. Every anthropologic behavior in the water system requires energy. Water is pumped for surface and ground for irrigation. Nearly 95% of the total cropped land has been brought under irrigation in the country (AIS, 2018). Irrigation is largely ground water dependent in Bangladesh, where surface water shares only 21% of the total water used for irrigation (FAO 2013). However, water is used for thermal cooling in power plants to produce electricity through burning fossil fuels. The share or amount of water used for such cooling in Bangladesh is not public, but power plants located on land are mostly dependent on surface and ground water for cooling. For simplicity, it will be assumed that the share of water used by different sources is similar to agriculture. On the other hand, modelling the water flow for energy, global and USA based data for water consumption in electricity generation can be used. Another important interaction of water centric WEF network to peripheral network which is the surrounding environment is to trace the amount of greenhouse gas or carbon dioxide has been released by such resource flow. Agriculture is one of the major contributors to global emission. Treating water involves energy use, which contributes to total emission which is required to be calculated in the model. On the other hand, water is used for hydro power generation which also directs a resource flow from water to energy. Thus, the mathematical modelling can be illustrated by fig. 15. Following equations describes the resource flow for water to food and energy systems. Each box represents resources, where resource flows are presented with directions and quantity.

$$\sum_{\substack{i=water\\source}}^{n} Water_{\,i} = \text{Total Renewable Water Inflows} \quad (1)$$

$$\text{Water Demand}_{year} = \text{Water}_{\text{food production}} + \text{Water}_{\text{electricity production}} \quad (2)$$

Where, $water_i$ represents the water sources, namely surface, ground and treated waste water. The energy requirement for such activities is shown in energy perspective of water, energy and food network.

The energy perspective of WEF network is depicted in fig. 16. The primary energy source and the final energy consumption are two critical aspects of energy in such modeling. Normally, energy processes in a country involves extraction, processing, production, generation, distribution, transportation, waste recycling and reuse. Extraction and refining fuel (gas, coal and oil) or transforming renewable energy (Hydro power and bio fuel) are often water incentive process. In Bangladesh, water or fluid intensive natural gas extraction (enhanced recovery or shale gas) method is not used. Traditional natural gas is less water consuming than shale gas. There is only one operational coal field, which

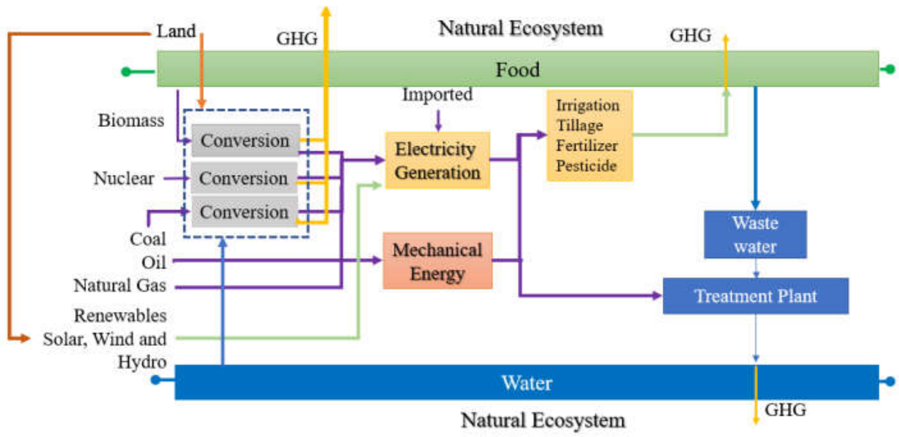

Figure 16: Energy perspective of WEF network.

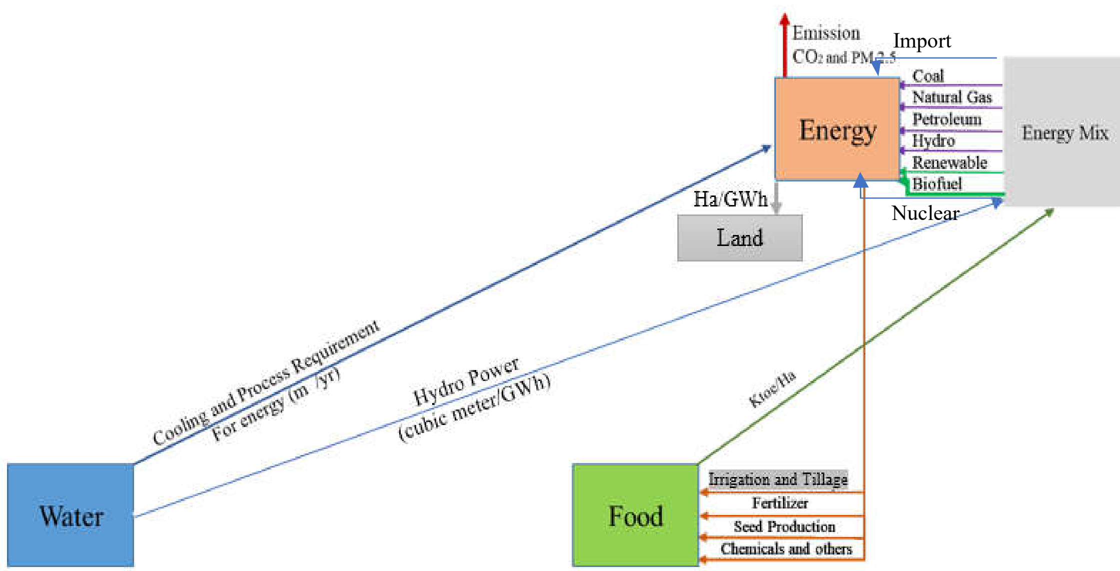

Figure 17: The resource sub-systems of energy in WEF resource network.

has limited reserve and mainly used for electricity production. Moreover, the only oil production facility, Bibiyana plant, which contributes to 1600 barrels per day production consumes insignificant amount of water. Although, data on water usage for energy extraction is not available for Bangladesh. Moreover, Bangladesh is net importer of primary energy. So, the water use for energy extraction and processing is quite limited compared to aggregate amount of water used in agriculture. Energy consumption also contributes to GHG and carbon emission which has adverse effect on the food production and water system via peripheral nexus, i.e. air and land.

As the scope of the study is focused on modes of final energy production and what will be the quantifiable impact on food and water, the extract and processing of the primary energy has been excluded. The net land, water required for cooling, processing as well as net emission from such production of electricity from power plants to be set on 2030 and 2041, mentioned in PSMP and announced by Power Division of Bangladesh, will be estimated. According to the report of IEA, Bangladesh receives a sizable portion of its primary energy from the biomass, produced from agricultural and municipal waste (around 23% of the total primary energy consumption) (IEA, 2018), but there is only one commercial facility in the country which uses biomass for electricity production. For the model, it is assumed that, the net water requirement for producing biomass is included in the water productivity of crops which limits the traditional water requirement for bio-fuels such as bio-ethanol and bio-diesel. Thus, in the model, the energy food interaction covers crop specific energy demand which covers energy input for irrigation, fertilizer, pesticides and chemicals (GJ/hector), land required for technology specific electricity generation (GWh/hectare) and emission (Tonnes/GWh), emission due to primary fuel consumption (diesel for mechanical energy input, natural gas for fertilizer and chemical production).

The model excludes fuel consumption for food transportation and import; thus, the model is more focused on static interactions of resources. Water is also used for hydro powered electricity production, which serves as inflow in the energy resource network (GWh/billion cubic meter, BCM). Bangladesh has only one large operational facility for hydro-electricity, and setting up more of such facility will withdraw surface water from the available sources of water. Electricity generation via nuclear facility is also water and land intensive compared to renewable energy sources (Strata 2017). Bangladesh also imports electricity from neighboring country which reduces the pressure on water, emission and land with the expense of self-sufficiency. Fig. 17 depicts simplified cross sectoral resource flow in units from energy perspective in units across WEF network for the model.

The food production perspective in WEF interaction has been shown in fig. 18. The food is characterized here as major crop production of Bangladesh which includes 4 major and minor cereals, one cash crop, vegetables, sugar and oil seeds which are grown in 90% of total arable land of the country (AIS, 2018). The annual food product demand is assumed as total raw demand of food for animal feed, industrial demand, human consumption and seed for future cultivation. Crop production activities include irrigation, tillage, harvesting, storage transportation and disposal of food waste. For this study, the resource inflows from energy and water to crop production is to be analyzed to quantify resource interactions across sectors. Agriculture is highly water and land, but low energy intensive sector, where, the energy consumption is largely connected to irrigation process and fertilizer production. The water efficiency is directly connected to energy used for irrigation, thus lowering water footprint can contribute to more energy demand and emission (Wakeel et al., 2016). Moreover, increased food production through agricultural intensification contributes to degradation of quality of water in downstream through agricultural runoff polluted with fertilizers, pesticides and manure from farm lands (Mirza & Hossain, 2005). Thus, using treated waste water for agricultural production will reduce the impact of water pollution and stress on water source with additional burden on energy and emission. For Bangladesh, the energy intensity for crop production is low compared to developing countries and largely dominated by fertilizer (Khosruzzaman et al. 2010). At the same time, around 50% of total fertilizer and pesticide demand is met by import, thus the stress of energy input for crop production has been shifted outside the country according to fertilizer industry report of Bangladesh in May 2017. According to PSMP 2016, Bangladesh is planning to shift its dependency on biomass as primary fuel for rural community and not planning on producing bio-diesel or bio-fuel, still, the amount of crop residue and waste produced per year has a huge potential to contribute to the national energy mix (Islam et al. 2014). In rural parts of the country, agricultural crop residue is being used for cooking and heating and contributes in fulfilling primary energy demand (Huda et al. 2014) which has a potential of more than 20000 K toe. It is hard to calculate how much energy is being used for fertilizer and chemical production. The research community uses energy co-efficient to calculate the energy input for crop production. In this way, energy contribution from fertilizer and chemicals can be used for analyzing the net energy input for specific crop production per hectare of land (Khosruzzaman et al., 2010). Nasim et al. (2017) discussed the detailed cropping pattern of Bangladesh which tabulated 316 type of cropping pattern in 2014-15 where rice dominated 17 different cropping patterns were seen to be practiced in 4961 k Ha land. Seasonal cropping pattern was seen for cash crops, wheat, and pulses. Sugarcane, spice, condiments, maize, oil seeds and vegetables are produced more than once a year. The net cropping area is calculated diving total land use for domestic production divided by the cropping intensity for that crop. The cropping intensity is calculated using total cropped area divided by net cropping area.

$$\text{Cropping intensity} = \frac{\text{Total Cropped Area}}{\text{Net Cropping Area}} \tag{3}$$

Where, total cropped area = 1 × Single Cropped Area (SCA)+ 2× Double Cropped Area (DCA) + 3× Triple Cropped Area (TCA)+ 4× Quadruple Cropped Area (QCA) and net cropping area is approximated to SCA+DCA+TCA+QCA (Nasim et al. 2017).

National cropping intensity for Bangladesh was 1.94 in year 2016, where, rice was one of the most dominated crops in land use and number of times cultivated over year (AIS 2018).However, for energy input calculation, total cropped area was used, whereas for water demand estimation in the model, water productivity was used. Fig. 19, shows the conceptual resource flows for food centric WEF network. Table 7 summarizes resource flows within described local resource subsystems for water energy and food. Each resource flow has been denoted as vector, representing the direction of the resource flow, characterized by the factors that drives the flow, indicators of such resource flow, specification defining the flow in units. As per resource subsystems and flows described above, the model development is connected to two additional biophysical resources, land

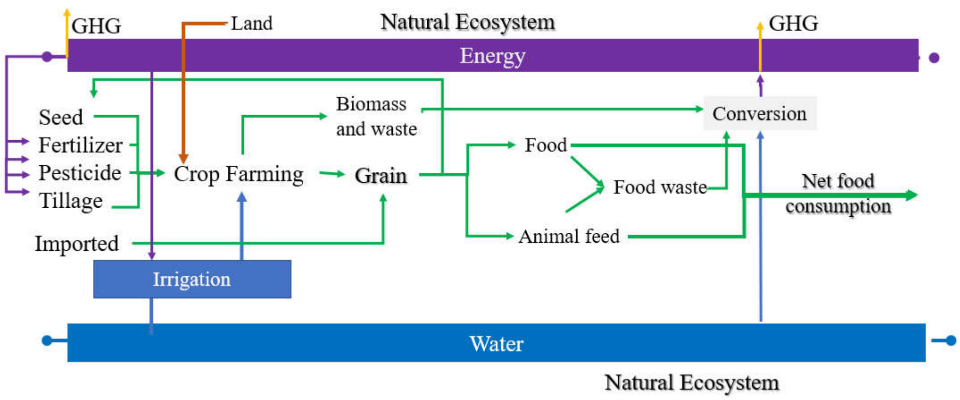

Figure 18: Water perspective of water energy food network.

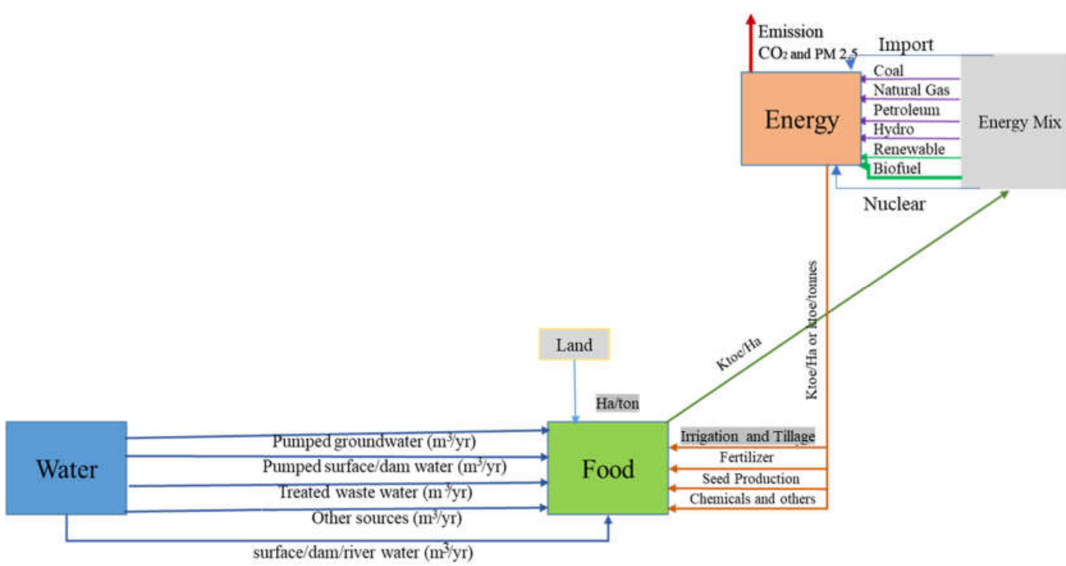

Figure 19: Food resource subsystem connected to water and energy systems.

and air, as a part of the peripheral nexus. So, the assessment of land demand and carbon dioxide emission to air in terms of resource flux are also tabulated. Vectors defined as

W_O, F_O, E_O, L_O are represented as water, food, energy and land resource outflow respectively whereas W_I, F_I, E_I are represented as water, food and energy resource production respectively. Vector CE defines carbon dioxide emission associated with to any driving factors. The driving processes are divided into three major processes, water, energy and food. The indicator defines which activity associated with the process.

Table 7: Resource flow measurements and specifications

Resource flow vectors	Driving Process	Indicators	Specifications	Units
W_O	Food Process Energy Process	Food Production Electricity Production	Crop specific water productivity Technology specific water consumption for electricity generation	Mega tonnes/BCM BCM/TWh
L_O	Food Process Energy Process	Food Production Energy Production	Crop specific arable land requirement Land requirement for electricity production	Hectare GWh/Hectare
Resource flow vectors	Driving Process	Indicators	Specifications	Units
E_O	Food Process Water Process	Food Production Treated Waste Water Production	Crop specific energy input from- 1. Fertilizer 2. Pesticide 3. Irrigation: Diesel 4. Tillage Energy required for producing water from waste water	MJ/Ha GWh/BCM
F_O	Energy Process Food Process	Energy Production Food Consumption	Energy produced from biomass a) Human consumption b) Animal feeds	GWh/Tonnes Mega Tonnes

Table 7: Continued

Resource flow vectors	Driving Process	Indicators	Specifications	Units
W_I	Water Process	Water Production	Water inflows from different sources 1. Renewable surface water 2. Renewable ground water 3. River flow 4. Rainfall 5. Treated waste water	BCM/year
E_I	Energy Process	Energy Source	Electricity 1. Coal 2. Oil 3. Natural Gas 4. Nuclear 5. Import 6. Hydropower 7. Solar Power 8. Wind Power 9. Biomass and waste Energy from primary sources: Oil	TWh MJ
F_I	Food Process	Food Production	Crop specific food production: Ten major crops 1. Rice 2. Wheat 3. Potatoes 4. Maize 5. Jute 6. Pulses 7. Oilseeds 8. Sugarcane 9. Vegetables 10. Spices and Condiments	Mega Tonnes
C_E	Food Process Water Process Energy Process	Food Production Treated Waste Water Electricity Production	Emission from burning fossil fuels for 1. Irrigation 2. Fertilizer 3. Tillage 4. Pesticides Emission due to electricity use Carbon footprint for each type of electricity generation process	Tonnes/MJ Tonnes/TWh/ BCM Tonnes/TWh

4.3.1 Framework for Interconnected System of the Systems

Having defined the perspective models for each resource in WEF network and corresponding resource flows among them, the framework of system interconnection for WEF network for Bangladesh has been introduced in fig. 20. For expressing resource flows through a set of equations, equation 4-13, several assumptions were made to

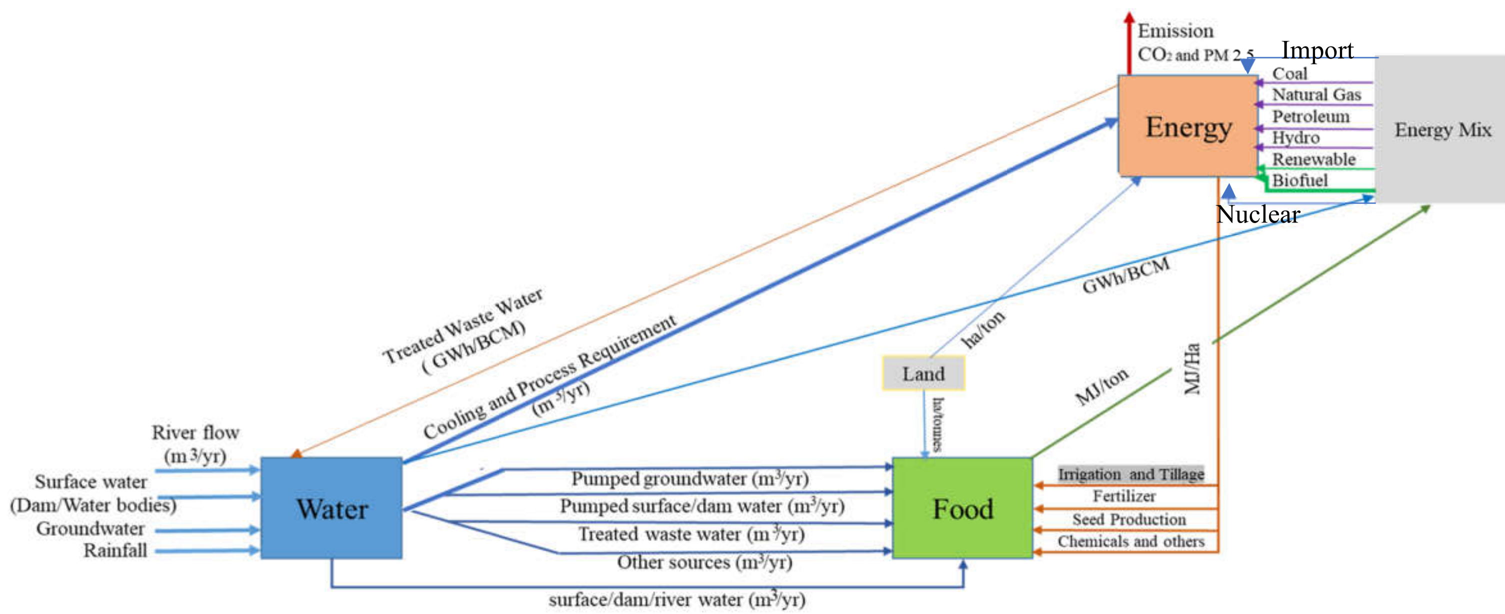

Figure 20: Developed framework of system interconnection for water, energy and food resource network in Bangladesh. Each link indicates input and output to individual resource system. The links has been identified in terms of units as input and output adopted from Daher and Mohtar (2015).

simplify the complexity of the model being developed. These assumptions, few of which have already been mentioned in defining the resource subsystem, will be described, followed by the set of equations developed to quantify the resource flow vectors and the overall impacts.

Assumptions and Limitations

1. The food resource balance only includes the food demand for ten major crops which constitute 90% of total agricultural production for Bangladesh. The demand for these crops includes domestic production and import of such crops from abroad, thus, includes the total demand for human consumption, animal feed and industrial demand. As, through this model, the total demand for food in 2030 and 2041 to be calculated, a population adjusted food demand has been assumed. The model will have the flexibility to adjust the food demand for future based on current food consumption pattern. The yield of ten major crops is highly dependent cropping pattern and share of high yield or low yield 2014). For simplification, the average yield of each of the major crops was used in the assessment process (AIS, 2018)

2. The energy required for each crop has been calculated from 4 different aspects, direct energy input from irrigation and tillage, indirect energy input from fertilizer and pesticide. These energy inputs vary significantly based type of crops, places and irrigation process (Rahman and Kazal, 2015). As the model will be designed to take 10 major crop production into account, crop specific national data is hard to reach, in these cases, the

model is dependent on data from different Asian countries for similar crops. The availability of more local data (energy input for different crops, cropping intensity for specific crops) would provide more refined results. The intervention of new and efficient agriculture technique, which might require less resources can also be integrated in the model, simply by changing resource inflow values.

3. The energy network in the model is divided into two major types, primary and final energy, i.e. electricity consumption. The direct energy input to agriculture, according to the prevailing practices comes mostly from diesel fuel, only 10% of the total direct energy consumption comes in form of electricity (IEA 2018). On the other hand, waste water treatment facilities use electricity to treat water.

For this model, it is assumed that the electricity supply is coming from the total electricity balance of the nation, generated from 9 different primary sources, coal, gas, oil, nuclear, imported electricity, biomass, hydro power, wind power and solar power. Changing in the share of electricity coming from each source will not change the amount of total electricity in the grid, but it will have impact on water use, land use and emission based on the generation characteristics for each technology. The impact on soil, air or water quality due to such technology has been kept out of the scope of the model. The net electricity demand has been fixed to national planning for 2030 and 2041.

4. Resource inflows among subsystem is based on empirically based data, published in different international journals and national publications.

5. The tool assumes linear relationship among in resource flow among systems which may deviate slightly from the reality. It simulates the impact on resource requirement in future, according to the long-term planning of the country, based on the prevailing resource flow characteristics. The central idea of the model is to project what may happen to the resource system if the country keeps executing its development planning, what are the adverse impacts and pushing resources to the national resource threshold. Thus, the model serves as a framework to project resource stress and risk associated with a long-term planning.

6. The model has two pivots, food and energy. The food demand will grow as the population grows, whereas the electricity generation targets for the country has been kept fixed to match its long-term perspective planning for energy. The model has been developed for national scale, so it cannot capture the advantage of producing different products for specific locations. It would have allowed better assessment for production in the WEF network.

7. The model excludes financial components. The government of Bangladesh has already set long term planning for power system and water body development. As the model is being developed to identify any resource stress in WEF interaction in future, financial

concepts such as net present value, interest, elasticity of food, cost insurance and capital investment to assess the financial efficiency of an alternative development.

8. Different risks and resource stress associated with any developed scenarios can be assessed quantitatively through the model. The model developed will help us to rapidly assess the resource stress and risks. For instance, if a shift electricity production, from fossil fuel to renewable might result in least emission and water consumption at the cost of land. Crops which require less water, may have low yield, thus the production of such crop might be lower. High yield crops might be season dependent, thus harvesting a crop twice might be difficult. Some crops are location specific, thus the production of such crop might be limited. Using same amount of land for producing more crops might increase the energy input, water demand for cultivation. Thus, different scenarios can be evaluated through the model to chalk out the synergies and trade-offs. Such rapid analysis can help us to realize hotspots and provide a hint for revisiting long-term planning in a more connected manner.

4.3.2 Mathematical Representation of Resource Flow

The mathematical representation of resource flow has two broad sections, resource inflow and outflow. As in the table 2, all resource flows are expressed in terms of vectors and units with specifications. Equation 1 and 2 have already been shown in such manner. In this part, resource inflow and outflow equations will be shown in bilateral representation, i.e. water to food, food to water, energy to food, food to energy, water to energy and energy to water. Moreover, how such resource flow has impact on its peripheral network with land and air.

Water: inflows and outflows

Water inflows have been expressed in equation 1. The quantity of water in renewable water reserves varies over time. In wet season, a little irrigation is required to produce crop. In dry season, the food production in Bangladesh becomes ground water dependent (Gain et al., 2014).

Water to food

Water is required food production. FAO uses water productivity (WP), also known as crop per drop which can be used to calculate the net water requirement for producing a particular crop. WP significantly varies spatially. To connect the water outflows to food production can be assessed by simply multiplying WP with the amount of a crop domestically produced (Amarasinghe et al, 2014).

$$W\_O_F = \sum_{jth\ Crop}^{j=10} w_j \times Crop_j \qquad (4)$$

Where, w_j billion cubic meter (BCM) water required for per mega tonnes (MMT) of $Crop_j$ production which is opposite of water productivity (MMT/BCM). According to Mekonnen and Hoekstra (2010), water for crop production comes from green, blue and grey water sources. Thus, source specific water inflow can help us realize which water sources be under stress. According to FAO 2008, 79% of the irrigation water comes from underground while the rest comes from surface water. The country has a very limited capacity for producing treated waste water for agriculture.

Water to energy

Conversion of primary energy to electricity requires water for processing. Coal, oil, gas and nuclear energy requires water cooling to produce electricity. As the model has been described, it has nine sources of electricity. Consumption of water for energy conversion is technology dependent (Larsen and Drews, 2019). For the model development, average medians of water consumption for energy conversions in power plant. For renewable energy sources such as hydroelectric power generation, the water consumed for electricity production is much higher (Mekonnen and Hoekstra, 2011). As it has been discussed, water footprint in biomass and waste production in Bangladesh is already been calculated in water for food inflow, but the processing and conversion of electricity from dry biomass require less water (Larsen and Drews, 2019). Thus, the total outflow of water to energy can be calculated through equation (5).

$$\mathrm{W\_O}_E = \sum_{kth\ energy\ source}^{k=9} w_k \times Energy_k \qquad (5)$$

And, w_k is the water consumed in BCM per TWh of electricity production from kth energy source.

Energy inflows and outflows

As mentioned earlier, the total energy inflows in the model has two parts, electricity and primary energy source for agriculture and water. Electricity comes from an energy mix and the primary energy for mechanical input and irrigation comes from diesel.

Energy to water

Energy is widely used for treating waste water and desalinization. As the model is more leaned towards using treated waste water for peri urban agriculture as the stress on ground water in such areas are high and water reuse can alleviate the pressure on ground water.

$$E\_O_W = E_{TWW} \times TWW \tag{6}$$

Where, E_{TWW} is the energy required for treating per BCM of waste water and TWW is the amount of waste water in BCM.

Energy to food

Typical energy input for crop production comes from human labor, mechanical power source, seed, chemical fertilizer, pesticide and irrigation. Following formulas are used for calculation of the energy inputs for each crop and then added to calculate the total energy input.

$$\text{Energy input for each crop}_i,\ EF_i(MJ/ha) = E_F + E_P + E_I + E_S + E_T \tag{7}$$

Where, E_F = Energy input (MJ/ha) from fertilizer for $crop_i$;

E_p = Energy input (MJ/ha) from pesticide for $crop_i$;

E_I = Energy input (MJ/ha) from irrigation for $crop_i$;

E_S = Energy input (MJ/ha) from seed for $crop_i$;

E_T = Energy input (MJ/ha) from tillage/mechanical means for $crop_i$;

For simplicity, it is assumed that seed is collected from the harvested crop, thus, the net energy input from seed is zero. In Bangladesh, most of the lands are used, on average, twice a year for crop production. Hence, the energy input to crop production, is related to total cropped area for each crop. The total cropped area for each crop can be used to convert the energy input for total domestic production. Moreover, Bangladesh currently imports more than 50% of total fertilizer and pesticides (Fertilizer Industry of Bangladesh Report 2017). Machinery used in cropland are operated by diesel whereas the pumps used for irrigation are run by both electricity and diesel. Thus, to calculate the domestic energy input to crop land, equation (7) can be modified to:

Total energy for food production, $E\_O_F = \sum_{j=1}^{j=10} (E_{I,j} + E_{F,j} \times (1\text{-Import\%}) + E_{P,j} \times (1\text{-Import\%}) + E_{T,j}) \times$ Total land used for $Crop_j$ in hectares (8)

Food inflows and outflows

In WEF interaction model, food is the most resource consuming resource, whereas a small portion of it (food waste, bio mass) is currently being used for electricity production, although the potential of generating electricity from this source is huge. The resource flow of food from energy can be calculated, whereas resource flow to water cannot be estimated through simple linear relationship and the volume of the flow is insignificant compared to other inflows to water.

Food to energy

As mentioned earlier, biomass and waste produced due to food production is a potential source of primary energy. The conversion of such energy to electricity can be seen as food flow for energy. However, in the model, the energy flow to water and food production is considered, which is largely fuel oil and electricity dominated. For simplicity, in the computational model, the maximum limit for electricity production from dry biomass has kept to 9400 K toe which is equal to the total primary energy input from biowaste produced in Bangladesh in 2016 (IEA, 2018).

Land use for food

Before expressing the land usage for food production in equations, it is essential to consider how to convert the total cropped area to net cropped area for each crop to be produced in the country. A cultivable land may be either cultivated or remained fallow throughout the year. If a crop is produced in a piece of land two times over a year, then the net cultivable land is the land itself while the total cropped land will be twice the amount of land. Out of ten major crops in the country, rice is produced on an average more than twice a year, resulting in total cropped land of 11 Mha which is 2.5 Mha higher than total cultivable land in the country (AIS, 2018). Agricultural land is also used for annual crop production such as fruits and flowers. Total cropped area can be found by dividing total domestic production to national yield of that crop, shown in equation (9). The national net cultivable land is calculated by dividing total cropped land by the cropping intensity defined in equation (3).

To compare whether the net land used for agriculture surpasses the total agricultural land of the country which is the available land resource for agriculture, land required for all the crops considered here in the model should be converted to net cropped area (NCA) used by each crop. In this model, the cropping intensity for ten major crops was calculated to estimate NCA. In order do that, 317 cropping patterns showed by Nasim et al 2017 was used as a reference for calculation. For instance, a rice-fellow-rice crop pattern is a dual cropped land for rice with NCA of 7000 ha, so the total cropped area for rice from that pattern will be double of NCA. A rice-jute-vegetable pattern with NCA of 3500 ha, has cropping intensity of three as each crop used the entire land once. Thus, from different cropping pattern, the net cropped land and total cropped land were calculated for ten major crops. Then, following the equation 3, cropping intensity for ten major crops of Bangladesh was calculated individually. This can provide us a hint on net cropped land used for agriculture and compare the amount of land with national agricultural land limit. Equation (10) shows the conceptual equation for estimating net cropped land required for food production, i.e. land resource flow for food.

$$\text{Total Cropped Area for Crop}_i = \frac{Total\ Domestic\ Production\ of\ Crop_j}{Yield\ of\ Crop_j} \quad (9)$$

$$L\_O_F = \sum_{1}^{j=10} \frac{Total\ Cropped\ Area\ for\ Crop_j}{Cropping\ Intensity\ of\ Crop_j} \tag{10}$$

Land to energy

As mentioned in the energy perspective of WEF interaction, land used electricity generation is to be calculated here. According to the land footprint for energy, calculated for US electricity production, the land requirement for energy includes energy plant land use, resource production land use, land use for transportation of fuel and storage land use. So, the land footprint for electricity generation from a primary energy source can be written as:

$$L\_O_E = \sum_j \left(E_p + E_T + E_S + E_R\right) \times Volume\ of\ Electricity\ Generation\ for\ Energy\ Source_j \tag{11}$$

Where, E_P, land required for setting energy plant (Hectare/MW);

E_T, land required for primary energy transmission (Ha/MW);

E_S, land required for primary energy source storage (Ha/MW);

E_R, land required for primary resource production or extraction.

Bangladesh is more dependent on imported fuel, land use for resource production has been left out of the calculation. The future plan for setting power plants are situated mostly in the coastal plains on the south-eastern part of the country. Thus, the transmission of fuel for those power plants are less likely to interact with agricultural land. The land acquired for setting two coal based power plants (2×600MW) in Matarbari island, a coastal island, was 1414 acre, resulting in 1 acre per MW of power generation and storage of coal sources, which is close to land footprint compared to USA, 1.17 acre per MW from coal (Strata, 2017). For this model development, the land footprint, calculated for electricity production has been used.

Food to emission

Energy flow to produce food involves conversion of primary energy source. For instance, the diesel fuel combustion can be expressed as fossil CO_2 emissions with equivalent of 2764.2 gL^{-1} (Pishgar_Komleh et al., 2011). Also, the machinery and fertilizer supply terms can be expressed in terms of the fossil energy required to manufacture and transport them to the farm with CO_2 equivalents of 0.071 kg/MJ and 0.058 kg/MJ for machinery and chemical fertilizers, respectively (Pishgar_Komleh et al., 2011). Thus, the carbon emission from food production can be mathematically represented by changing equation (8) for emission:

Total Emission for food production, $C\_E_F = \sum_{j=1}^{j=10} (E_{I,j} \times C\_E_{I,j} + E_{F,j} \times C\_E_{F,j} \times (1\text{-Import\%}) + E_{P,j} \times C\_E_{p,j} \times (1\text{-Import\%}) + E_{T,j} \times C\_E_{T,j}) \times$ Total land used for $Crop_j$ in hectares. (12)

Where, $C\_E_{I,J}$ = CO_2 emission from energy use in irrigation;

$C\_E_{F,J}$ = CO_2 emission from energy use in fertilizer;

$C\_E_{M,J}$ = CO_2 emission from energy use in pesticide;

$C\_E_{T,J}$ = CO_2 emission from energy use in mechanical energy input/tillage for crop $_j$;

Energy to emission

In this interaction, the amount of CO_2 released from each electricity producing sources can be used to calculate the emission from energy portfolio. The energy mix for electricity production of Bangladesh includes sources from fossil fuel to renewable sources. The carbon footprint for each energy sources can be used to calculate the total emission from electricity produced from different sources (WNA 2011). The following equation is used to calculate the total emission:

$$C\_E_E = \sum_{jth\ energy\ source} C\_E_j \times Volume\ of\ Electricity\ from\ source_{\ j} \qquad (13)$$

Where, C_E_j = Carbon footprint for using jth energy source.

Resource limit and uncertainties

Within WEF interaction, land and water resources have physical limit. Bangladesh has total of 8.5 Mha of agricultural land and 105 BCM of renewable water reserves, of which 21.09 BCM is under ground. The agricultural land is also subjected to annual land loss at 1%. If this is accounted, the arable land for food production will decrease to 7.42 and 6.64 Mha in 2030 and 2041 respectively. Moreover, Bangladesh is one of the most vulnerable countries to sea rise due to climate change. If the sea level rises by 1m, Bangladesh might loss 1.7 M ha of land, which may result in displacement of people from the coastline to main land and loss in cultivable land (Impact of sea level rise in Bangladesh, n.d.).

4.3.3 Data Source, Description and Processing

Data availability is critical in estimating the resource flow and selecting the nexus research approach (Zhang et al., 2019). In Bangladesh, data from open databases (annual report, statistical publications etc.) to conduct nexus research is not readily available at national level, for instance, there is no national data source for water consumption or emission in electricity production or crop specific energy consumption in agriculture. Thus, on search for local characteristics of resource flow, data is mostly collected from published journals and research work. Country specific data published by international organizations namely FAO, Aquastat, USAID and sources such as index mundi has also served as primary data source for setting national demand for food and domestic production. In absence of country specific data, for example, emission from electricity generation or burning fossil fuel, either global or regional data were used. Some data is being estimated from relative data source available such as cropping intensity for different crops to calculate net cropped area per crop in Bangladesh. Table 8 tabulates sources of primary, and secondary data for calculating resource flow across core network, i.e. water, energy and food, as well as core nexus to peripheral interaction with land and emission. Fig. 21 and 22 show the comparative resource flow for all crop items found from the data sources. Table 9 and 10 tabulate crop and energy source specific resource flow respectively. From the data, it can be realized that cereals and jute are more water, energy and land demanding resources compared to other major crops. Thus, increasing self-sufficiency in cereal will put more stress on those resources. Rice has more temporal and spatial coverage on arable land and comprises 80% of total cereal mix in the country. As other crops are season dependent,

Table 8: Data sources for calculating resource flows

Item	Data type	Information	Primary Source	Secondary Source
Food demand	Domestic Production Import Future food demand prediction	Crop specific national demand Food demand adjusted to population growth adjusted for 2030 and 2041 Population growth	AIS 2018 AIS 2018	- Index Mundi Islam and Talukder, 2017 Roser, 2013
Energy Demand	Electricity generation Energy required for food production.	Volume of electricity generation Energy input through fertilizer, tillage and pesticide	PSMP 2016 -	- Khosruzzaman et al., 2010; Khan and Hossain, 2007; Abdi and Morteza, 2012
Water Demand	Water resource availability Water Productivity Water footprint for electricity production	Source specific water inflows and reserves Crop specific consumptive water usage for per ton production. Technology or source consumptive water required for per TWh electricity production.	Nasim et al., 2014 -	- Amarsinghe et al 2014; Wakeel et al., 2016 Spang et al., 2014 Larsen and Drews, 2019
Land Demand	Land for food production Estimated Land required for electricity production	Yield Cropping intensity Total cropped land per crop, Net cropped land per crop Land required for electricity production, fuel transmission and storage	AIS 2018 AIS 2018 AIS 2018 -	Nasim et al., 2014 Nasim et al., 2014 Strata 2017
Carbon Emission	Carbon emission from agriculture Carbon emission from electricity production	Emission associated with energy use. Fertilizer and chemical import. Source and technology specific carbon emission from power plants	- -	Pishgar_Komleh et al., 2011 Fertilizer Industry Report 2017 WNA, 2011

rice as a single cereal and crop takes the larger share of much of the production. For energy input calculation, it is assumed that 50% of the total fertilizer and chemicals are being imported, thus the virtual import from emissions was excluded in crop specific emission calculation. It has already been discussed that the future projection for energy demand is vastly import dependent. Thus, extraction and processing for energy has been excluded from the resource flow. Data for source specific electricity generation has been re-estimated for generation and distribution purposes. According to national planning, biomass-based electricity generation is fully agricultural and municipal waste dependent.

Table 9: Resource flow for ten major crop production

Item	Yield MT/ha	*Cropping Intensity	Net Cropping Area in Mega Hectare	Water Productivity [1](MMT/BCM)	[2]Energy Input (GJ/Ha)	Emission in Mega Tonnes
Rice	3.089	2.5	4.48	0.44	13.2	5.07
Wheat	3.32	1	0.41	1.29	13.5	0.46
Potato	20.4	1	0.46	3.98	3.2	0.13
Jute	11.25	1	0.68	0.125	15.2	0.88
Maize	8.25	1.2	0.42	1	8.2	0.31
Pulses	1.02	1.5	0.67	0.71	3.1	0.19
Oil Seeds	1.14	1.5	0.53	0.71	5.9	0.28
Spices and Condiments	6.05	1.2	0.37	0.15	6.5	0.22
Sugar Crops	42.78	1.2	0.08	3.88	8.4	0.06
Vegetables	18.8	1.7	0.05	1.96	17.8	0.09

*Cropping intensity for each crop was calculated from data available Nasim et al 2017 [1] Water productivity (WP) expressed million tonnes per billion cubic meter water [2] Energy input calculated as domestic energy input from nationally produced chemicals and fertilizers

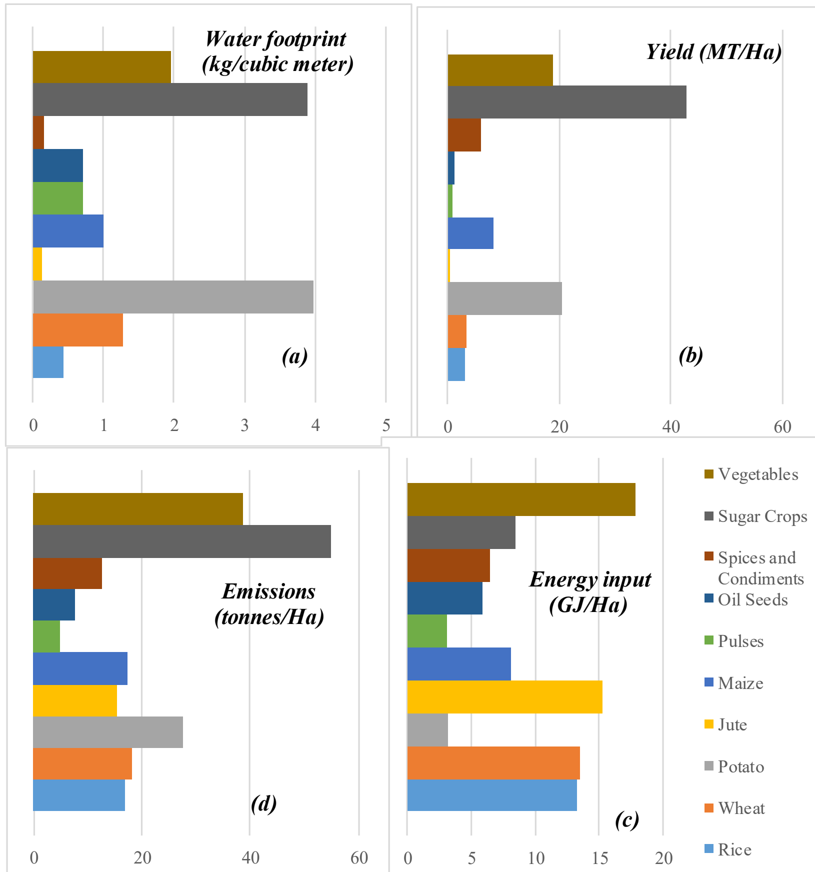

Figure 21: Resource flow a) Water footprint, c) Energy input and production b) Yield and d) Emission from different crops based on local characteristics.

Thus, for such source of energy, the water flow has already been taken in crop production calculation along with the land. The water consumption for each technology was taken as water consumed rather than water use to assess the net water withdrawal from water sources. For cooling and processing, the water withdrawal from different water sources is kept as same as agriculture.

Table 10: Electricity demand, resource flow and emission based on year 2016

Item	Electricity in MW	Share (%)	Land Use (Ha/MW)	Average Carbon emission (tonnes/GWh)	Consumptive water use (m^3/GWh)
Coal	200.0	1.56	4.9	580	1.8
Oil	4126.0	32.11	5	340	1.1
Natural Gas	7529.0	58.60	5	310	1.05
Biofuel	0.0	0.00	1	410	1.05
Electricity Import	600.0	4.67	0	0	0
Nuclear	0.0	0.00	5.1	0	1.15
Hydro power	230.0	1.79	127.6	0	10
Solar power	161.0	1.25	17.6	0	0.01
Wind power	2.0	0.02	28.5	0	0.001

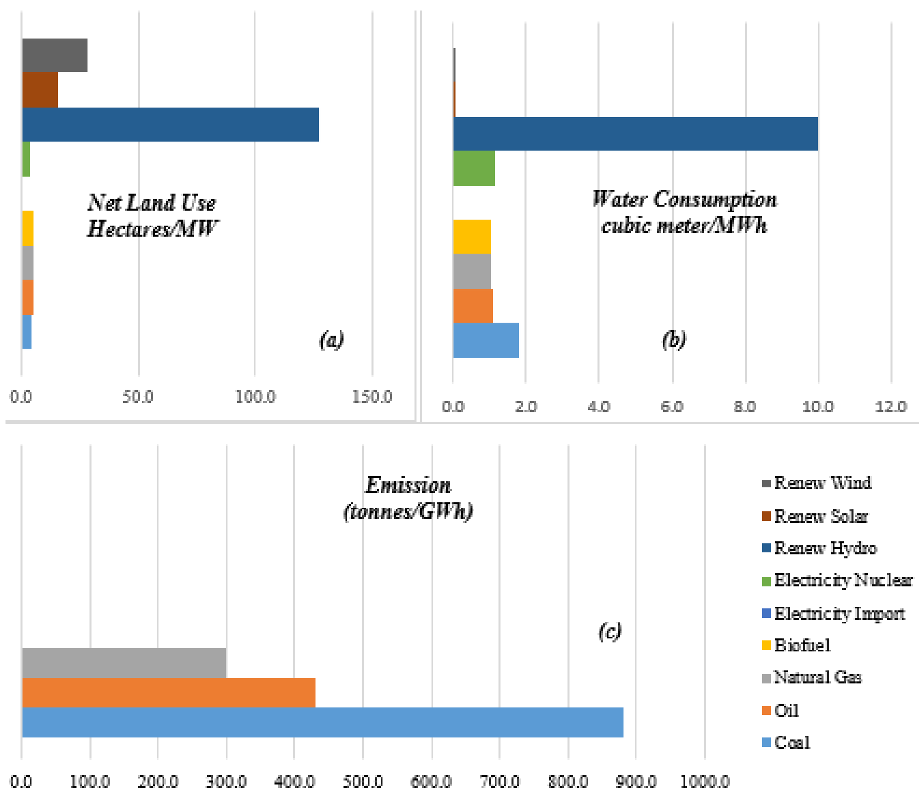

Figure 22: Resource flow for electricity generation based on global characteristic of electricity production. All resource inputs are taken as a mean of global resource flow for electricity production.

4.3.4 Tool Structure for the Model

As the model uses only linear equations, simple computational software such as Microsoft excel is the easiest, compatible and user-friendly tool. Related data was collected from sources mentioned in table 8. Data can be arranged as separate pivot spreadsheet for water, energy and food. The tool has three different parts:

a) Database for local characteristics; b) Input interface; c) Dashboard based on output.

Table 11: Input and output of the tool

Input	Output
Change in food portfolio: Volume and self-sufficiency for each crop	1) Volume of all major crop production 2) Import volume of food 3) Net water and land demand 4) Emission from energy input for crop production.
Change in Energy Portfolio: Share of different primary energy sources in producing electricity projected for 2030 and 2041.	1) Total land and water required for setting power plant facilities for different primary energy mix. 2) Total CO_2 emission from electricity generation. 3) % of renewable in total electricity generation.
Change in Water Portfolio: -Share of water among resources. a) Surface b) Ground and c) Treated waste water (TWW)	1) Water withdrawal from different sources 2) Energy required for treating waste water 3) Emission from TWW
Additional input to calculate the wholistic impact on resource flow: 1) Population growth 2) Annual land loss	1) Impact of volume of food demand 2) Impact on land for food and energy

Database for local characteristics contains data on resource flow. Input data has 24 options, changing %SS for ten major crops, % share of nine sources of energy and water along with 2 uncertainties, population growth and annual arable land loss rate. The database has the flexibility to update specific data for resource flow or balance. One spreadsheet is being built to provide the user interface for changing resource portfolio to observe the estimated change in output. A separate dashboard is being designed to show the results in graphical representation.

4.3.5 Connecting SDG Targets and NPIs

One of the objectives of this study is to connect assessment from the tool to sustainable development goal targets and national priority indices. As discussed in table 1(literature review), six national priority indices were related to corresponding SDG targets which also were also connected to the WEF core interaction. However, with the output from the model, the assessment of resource interaction can be connected two quantitative SDG indicators and NPIs. The assessment can also be used to quantify complete or a part of four SDG targets. SDG Indicator 2.2.1 and NPI 3 are mostly related to access to nutrition for children aged under 5. There is not any assessment which can be directly connected to such indicator. Moreover, indicators which are extremely dependent on expanding facilities and distribution, such as access to safe water for drinking (SDG target 6.1, NPI 17), sanitation (SDG target 6.2 and NPI 18) as well as access to affordable electricity (SDG target 7.1 and NPI 19). Two SDG targets (2.4 and 7.2) and NPIs (4 and 20) can be assessed from the output of the tool directly as the tool provides an assessment on total

Table 12: Connecting SDG targets and NPIs with model output

SDG targets and NPIs which cannot be assessed			
SDG Targets	NPI	Indicators	Remark
2.2	3	Reduction of stunning by 15% (2.2.1)	Self-sufficiency in food production cannot be decisively related to nutrition distribution
6.1	17	Proportion of population using safely managed drinking water (6.1.1)	This indicator is completely related to quality standard and access to drinking water. The model cannot be related to such indicator (UNSTATS 2017)
6.2	18	Proportion of population have access to safely managed sanitation and hygiene (6.2.1)	The indicator is related to the accessibility of people to sanitation and hygiene. (UNSTATS 2017)
7.1	19	Proportion of population have access to electricity (7.1.1)	This indicator is connected to the proportion of people having access to electricity, not volume of electricity production (UNSTATS 2017).
SDG targets and NPIs assessed directly			
2.4	4	Portion of agricultural area under productive agriculture (2.4.1)	Dividing total land used for food production by total agricultural land available in the country
7.2	20	Renewable energy share in energy mix (7.2.1)	Can be calculated directly from the model output (by volume and share in electricity generation)
SDG targets and NPIs which can be assessed directly from assessments			
6	-	Treated waste water (%)	Treated waste water used (%)
6	-	Fresh Water Withdrawal	Water withdrawal can be calculated as proportion of water withdrawn from available renewable water sources
7	-	Carbon emission from electricity production	Carbon emission from electricity production
2	-	Cereal Yield	Cereal yield (tonnes per hectare)

arable land requirement on food production and % share of renewable energy. There are a few SDG indicators which can be calculated from the output of the tool. Water use efficiency can be calculated from water used in per unit food production multiplied by the market price of the food. If market price of the food is available, indicator 6.4.1 can be calculated. SDG indicator 6.4.2 is connected to resource stress of water. It is simply the percentage ratio water withdrawn to total available water in a specific resource. The global SDG indicators also provide a country specific annual assessment for corresponding to different target (Sachs, 2019). Excessive use of blue or ground water for agriculture and energy has been an issue for research lately (Daohan et al., 2020). With growing population and economic activity, depending on single water source, will undeniably put stress. The tool allows to change the share of water according to sources. The fresh water withdrawal serves as an indicator for sustainable resource use which shows how much fresh water has been withdrawn from the internal renewable fresh water resources (SDG 6). The percentage of water reused also serves as a development indicator. Globally, around 50% water treated and reused is considered as sustainable water management. As in the assessments, scenarios include treated waste water share as a strategy, it is an opportunity to connect such assessment to this SDG indicator for SDG 6. Carbon emission depends on choice of energy sources and types of food to be produced which is relatable to tool’s input through a scenario, which provides the window for estimating the impact of a change in input to global indicator connected to SDG 7. In global indicator, carbon emission due to electricity generation is calculated in million ton emitted from tera watt hour electricity generation. However, the global standard does not match the sources mentioned in the SDG report 2019 (Sachs et al., 2019). For the assessment, the global average, according to IEA is considered as benchmark (475 gCO_2/KWh). The assessments can be extended to calculate the cereal yield of Bangladesh. As the input have ten different crop option with 2 major cereals and 1 minor cereal, the cereal yield can be calculated to see the impact on cereal yield for each scenario compared to global standard 2.5 tonnes per hectare of land.

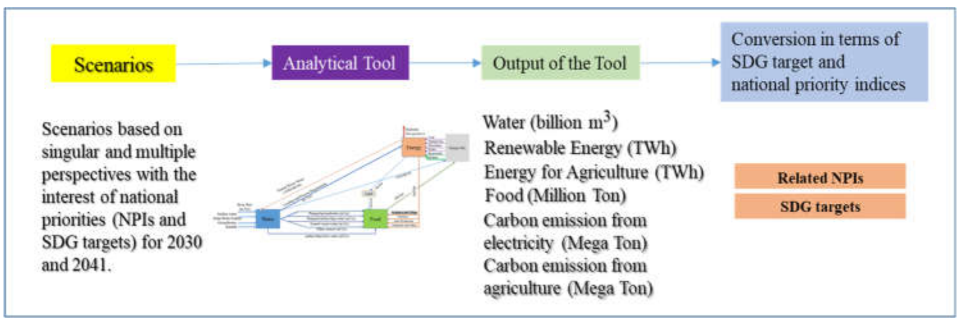

Figure 23: Structure of the tool.

Table 12 shows which assessment can be connected to which SDG targets, what additional data is needed to perform such assessments along with which SDG indicators cannot be calculated, formally assumed in the objective. The tool also serves as a platform form comparative assessments. The tool compares assessments of any scenario with the base year 2016, to show how much access resources will be needed in fulfilment of such scenario. Necessary assessments have been made for base year 2016 and kept fixed during comparative assessments. For any user input, the tool will simultaneously calculate resource requirements for 2030 and 2041 and compare the output with base case 2016. Thus, comparison between base year and year 2030 and 2041 will be seen on the dashboard. Table 8 shows all of the input options and calculated outputs. In order to provide a visual input to the computational tool, free microsoft excel is used. It provides the flexibility of changing input and simultaneously observe the change in output in visual form. The interface can change the input in excel, extracts results from it and provides graphical representation of the selected results. Fig. 23 illustrates the structure of the tool developed based on the defined resource flow of the model.

4.3.6 WEF Nexus Assessment Tool: Test Results

After building database matched with local resource, the estimated output based on input and resource flow for base case 2016 was compared with available data on 2016. For instance, for ten major crop production in 2016, the total amount of water usage, total energy input and the resulted emission are calculated and compared with data on such output, either available in national or international database or research publications. It is important to note that, net resource flow for food import is kept zero. Water demand estimation found significantly higher as the volume of rice and rest of the crop production had increased significantly. The consumptive water use for agricultural production uses ARIMA for calculating water requirements for each crop and have different estimated result compared to FAO 2008 data (Amarsinghe et al. 2014). Moreover, there is no fixed estimation for cropping intensity different crops. If the assessment is done using total cropped area, the total cropped will significantly higher than actual arable land according to equation 3. That is why, cropping intensity for each crop is being calculated by from the list of cropping pattern and net cropped area for each group of major crops, and tabulated in table 9. For ten major crops in consideration the aggregated national cropping intensity is 1.94, a little higher than aggregate cropping intensity of the model which is 1.92. National energy consumption has two perspectives, total primary energy consumption and finished energy consumption. For this model, the tool is used to calculate total land, water requirement and the emission resulting from choosing such energy mix. and estimated results from the model in comparison with available data are shown in table 14. The estimated result for emission was found close to the volume of emission from electricity generation, reported by IEA 2019. For comparing the land and water demand, no national or international data was found as per the author's knowledge. In IEA 2018 report, the imported electricity was not included in generated electricity data. If the data is included, the share of renewable energy will be lowered to 3% which is far away from nation's objective to raise renewable energy share in electricity production by 10% in 2030.

The calculation for water balance is a bit challenging through the model as it does not include recharge of ground and surface water sources from irrigation and other water usage in crop production (Amarsinghe et al., 2014). That is why, based on surface and ground water share mentioned in FAO 2008, the net demand for ground or blue water is substantially higher in estimation than the volume mentioned in FAO 2008. The results including total water demand energy and food as well as source specific water withdrawal(outflows) as % and volume are tabulated in the following table 15.

Table 13: Result from the developed model for base year 2016

Item	Estimated	Published	Source
Total Water Demand (BCM)	109.5	67.701	Amarsinghe et al 2014
Net Energy Input (PJ)	88.8	90	Alam et al. 2014; estimated
Total Land Demand (M ha)	8.03	7.94	AIS 2018
Total Emission (M ton)	7.67	-	-
Aggregate Self Sufficiency	85%	-	-

Table 14: Estimated results from the model and comparison for year 2016

Item	Estimated	Published	Source
Net Land Demand (M ha)	0.091	-	Estimated
Net Water Demand (BCM)	0.13	-	Estimated
Net Emission (*M Tonnes)	36.9	36.9	IEA 2019
Renewable Energy (%)	3.06%	3.06%	[1]BPDB 2016, estimated

[1]Bangladesh Power Development Board *Million

Table 15: Water resource inflow and outflow estimation

Sources (Outflow)	Estimated		Water Resource	Estimated	Reserve	Balance
Agriculture (BCM)	109.5		Surface water (BCM)	23	1206	1183
Energy (BCM)	0.07		Groundwater (BCM)	86	21.09	-64.91
Water usage share	Surface water 21% Groundwater 79% TWW 0%		TWW (BCM)	0	0	0

As the estimation of the model in estimation, showed fare accuracy but in some cases showed deviation, the tool also let the model compare its base case result to the result of any new portfolio input for energy, food and water, and tabulates results in terms of excess resource requirement, in % and volume, with respect to the base case 2016.

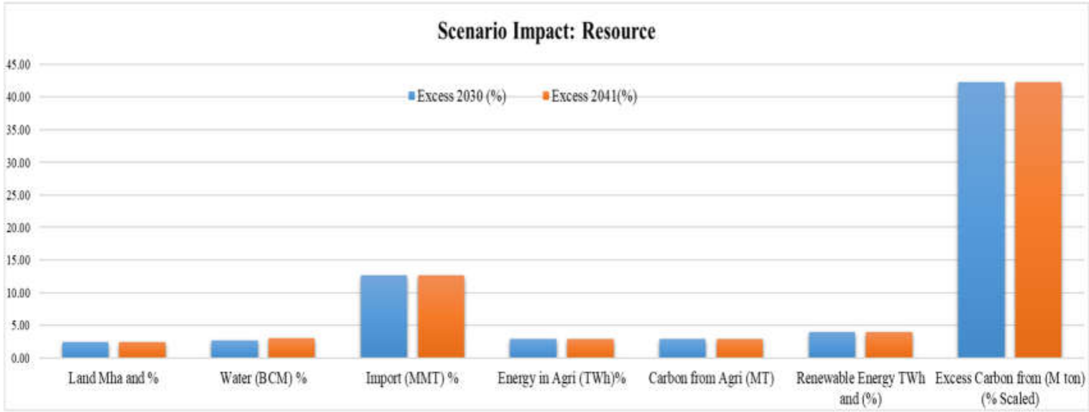

Figure 24: Increase in resource demand (shown in %) for attaining 100% self-sufficiency in rice and shifting energy dependency from natural gas to coal by 60% for electricity production assuming annual population growth at 0%.

Thus, the error or discrepancy present in the model estimation will cancel out and the margin of error will be less compared to estimated data. For instance, if we want to see what is the impact on overall resource system if the current primary energy input mix is shifted to 60% coal for electricity generation along with 100% self-sufficiency in rice production, where the domestic production for other crops and electricity demand remains the same for 2030 and 2041; the model will simultaneously calculate the resource flow and compare the result with base case 2016. Fig. 24 shows the scenario in bar graphic. Thus, the model is capable of showing assessments for different scenarios. If 100% self-sufficiency is desired in rice production, it will demand more land, water and energy input, thus increasing the land, water and energy demand but increase overall self-sufficiency in aggregate food production. Increased energy input involves more emission. However, choosing emission intensive primary resource, such as coal, for electricity production, will add significantly to carbon emission from electricity generation industry. The land and water footprint for coal is similar to other fossil fuel based electricity production, hence the impact on land and water in terms of volume is insignificant, although the adverse impact on environment due to air pollution from such sources is significant and complex, yet such assessment has been kept out of the scope of this model.

4.4 Scenario Development and Setting Assessment Parameters

The basis of the study is to identify whether policies developed in silos, coherently or incoherently, stressing the core resource subsystems and natural environment. It has already been shown that in pursue of individual goal, policies developed by ministries are not always demonstrating connectedness. As the developed tool is capable of assessing resource requirement and impact for each scenario involving decision in water, energy and food, both demand and supply, a conceptual scenario matrix can be presented as follows:

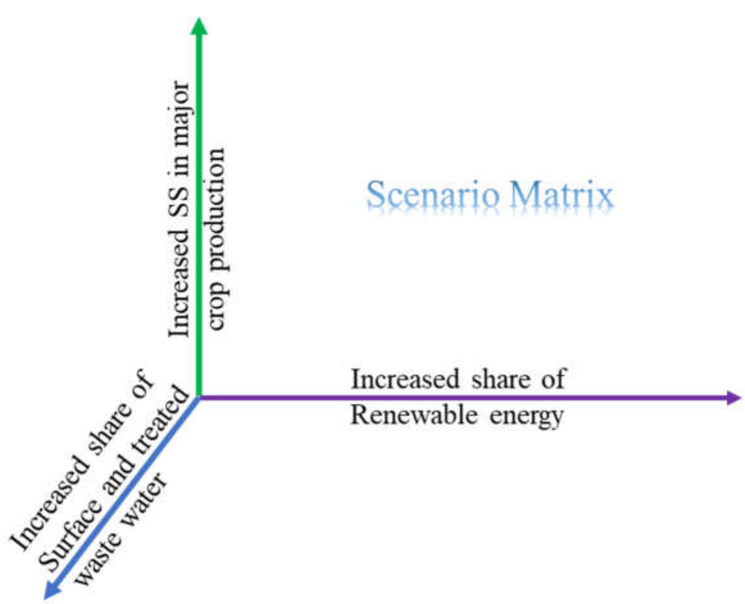

Figure 25: A conceptual scenario matrix for choosing scenarios.

In the matrix, scenarios can be chosen combining options from each of the resource system. Decision makers can pick one of thousand combinations and check it through the tool to decide whether the decision will yield favorable outcome in future, thus serve as a guide to decision makers. Once again, the financial impacts of a decision have been excluded from assessment. The government of Bangladesh has already promulgated budgetary framework for long term planning. The scenario development and related assessments can aid decision makers to show what are the implications for the decisions they have already taken for future as well as what are available options. To further explain, scenario-based framework, let focus on each of the different axes of the scenario matrix shown in fig. 25 and which considerations showed be kept in count.

Scenario development- food portfolio*:* Change in food sufficiency based on future demand has been shown in a downward axis in the fig. 25, where moving downward means decrease in %SS. By changing the percentage of self -sufficiency of food production for one or multiple crops in the food portfolio, food centric scenarios can be developed. More self-sufficiency attained in crop production implies less food dependency on import, where most of the major crops are produced locally under local characteristics of resource flow. For instance, wheat, has low yield in compared to global yield in Bangladesh. Thus, attaining 100% self-sufficiency in wheat will require more land than rice or maize. Moreover, the tool will be used to make an assessment for future demand of ten major crops (assuming similar diet pattern of base year 2016), try to reflect the impact of changing self-sufficiency of different crops based on future demand of food, thus assess the excess resource required in future for year 2030 and 2041. The population growth can be adjusted to low, medium or high variant for projecting total population of the country and the related food demand will follow. Land and water footprint for food production carries the base stress in populous countries. More production will take more land and water from resources as well as raise the demand for energy input, which in turn, will increase emission from agriculture as well.

Water portfolio: In the model, three major sources of water are considered, surface water, ground water and treated waste water. In the conceptual scenario matrix, moving from center to outward shows decreased dependency on ground water while increased share of surface water and treated waste water. Changing the percentage in total use for each of the three resources has different implications, such water availability, energy use and associated carbon emission. The tool has the flexibility to incorporate these changes in the assessment. For example, rice and jute have low water productivity, thus attaining 100% self-sufficiency in these crops will put stress on water sources unless the share of resource flow from different sources are being diverted. Thus, scenarios can be developed by changing the share of resource outflow among sources (e.g. 40% surface water, 50% groundwater, 10% treated waste water).

Energy portfolio: While moving along the energy row of the matrix, the shift for energy dependency from coal to cleaner energy has been represented. The model has nine different primary energy options to convert it to electricity. The share from each of the nine primary energy sources can be change for producing projected amount of electricity for 2030 and 2041 respectively at the input of the tool. As the future projection for electricity demand has kept fixed, energy portfolio is changed by priming shares to different energy sources. The tool allows changing the share of each of the energy input from 0 to 100%. The energy input associated with food production can be changed as Bangladesh relies on import of fertilizer and chemicals, which also implies the virtual import of energy and emission. Such assessment option can help to quantify net domestic emission for food production. Using the aforementioned scenario as input portfolio, the tool in turn assesses the following for each scenario based on local resource flow characteristics of Bangladesh-

1) Aggregate water outflow (BCM)

2) Aggregate energy outflow for agriculture and treated waste water (TWh)

3) Aggregate self-sufficiency for ten major crops (%SS and %Import)

4) Carbon footprint for domestic production and electricity production (Mega Tonnes).

5) Volume (TWh) and % of Renewable energy in the total energy mix of electricity.

4.5 Limitations in Developing Scenarios

The developed tool can serve as fluid in a sense that it can take different shape and sizes depending on specifics of a scenario. According to the tool structure, multiple number of scenarios can be created by varying food, energy and water portfolio. But not all assessments are practical. Importing 100% electricity, can reduce the stress on land, water and emission for energy production but not doable. Relying more on import for food will increase the dependency on other countries. Import initiatives also involve investments. On the other hand, 100% self-sufficiency can significantly increase stress on land and water sources. Producing electricity from clean or renewable sources might need more land than conventional energy production. Some scenarios have physical limitation to implement. For example, energy mix cannot be made 100% hydropower or solar power or wind power based because of its maximum generation capacity in the country (Uddin et al, 2019). Thus, implementation limitation for a specific scenario can make assessments possible by the model, but impossible to implement. Besides, the resource flow required for implementing a scenario can exceed the available limit of such resource. For example, 100% self-sufficiency for all major crops can exceed the limit of national arable land limit and available ground water for agriculture. The pressure on ground water can be reduced via treating waste water and make it available for peri urban agriculture. But recent studies showed that such water has detrimental impact of crop yield (Roy et al, 2013). Implementation of such scenario might face stakeholders i.e. crop growers' reluctancy. Moreover, crops are very soil type specific, which also makes a profitable and productive type of cropping pattern different from the traditional cropping pattern that crop growers used to follow (Nasir et al 2014). A shift from traditional cropping pattern to a new one requires stakeholders and bio-physical adaptation.

Shifting towards biomass and waste for electricity generation might face such restrictions. The rural community of Bangladesh is largely dependent on agricultural waste for cooking and heating (Uddin et al., 2019). Depending more on biomass for electricity production has two structural limitation, firstly, the practice of biomass for producing electricity in rural community is distributed, not centralized. Thus, electricity generated from such sources might require building of a transmission line are a way to feed the electricity to local grid. This will also take away bio mass from primary energy source, available for rural community. Hence, changing crop pattern or altering energy source have to be adaptable to stakeholders and society.

Last but not least, the institutional structure must be considered for pointing out the feasible scenarios. In Bangladesh, water resources are controlled by three different ministries, ministry of water resource, ministry of land and ministry of local government. While the former ministry covers water resource management of rivers and canals, ministry of local government has controls on water bodies while ministry of land has jurisdiction on land itself. Such interconnected water resource management have to be on agreeable terms in implementing a scenario. For example, for reducing dependency on groundwater and making surface water available for crop production requires joint planning from local government, ministry of water resource along with participation from ministry of agriculture. Currently, ground water is an unregulated resource for agriculture in rural areas, and controlling the use of such resource asks for multidimensional execution of planning rather than silo execution. So, execution of a scenario also needs to be screened through the institutional structure of government and local bodies.

4.6 Institutional Framework of Connected Stakeholders

Water, energy, and food are the key elements in the development of society and a necessity for living prosperously. Management and production decisions of such resources have both top-down, bottom-up, and cross-connected approaches. Any future planning must consider stakeholders in every layer of decision and institutions (Bassel et al. 2018). Thus, it is prudent to understand which institutions are potential stakeholders in implementing such a strategy and their degree of involvement. Fig. 26 shows the conceptual stakeholder map of WEF core network and peripheral network of Bangladesh. The outer circle includes the field level stakeholders, ranging from division under ministries, in decision making. The middle process (and subordinate institutions inside the box) connects administrative and operational institutions and bodies. The decision-making core includes cabinet, ministries, and Office of the Prime Minister (PMO) in final decision making, which involves passing bills and funding. In agriculture, the key stakeholder is the Ministry of Agriculture (MoA), which oversees Directorate of Agriculture Extension (DAE), Bangladesh Agriculture Research Institute (BARI), Bangladesh Rice Research Institute (BRRI) which are responsible for expanding agriculture through introducing high yield and hybrid agriculture practices. In contrast, Bangladesh Agriculture Development Corporation (BADC) and Bangladesh Agriculture Research Corporation (BARC) are responsible for irrigation and water management for agriculture. BADC provides technical understanding for irrigation and seed. The majority of long-term planning falls directly under DAE, BARI, and BRRI for agriculture expansion and increasing production by providing good quality seeds, salinity, and flood-resistant crop varieties, incentives to the root level farmers in the country. The primary decision-making power and policy recommendation come from the ministry of agriculture, and the subordinate institutes and agencies execute such decisions. However, some additional influential actors can place compelling demands on decision making such as farming communities, cooperative farm groups, non-government organizations, and local government institutions, who pass their opinion either directly or through administrative institutions or members of the parliament. Members of the parliament can carry such demands to cabinet either through parliamentary advisory committee or assembly. The Prime Minister has both political influence and highest executive authority.

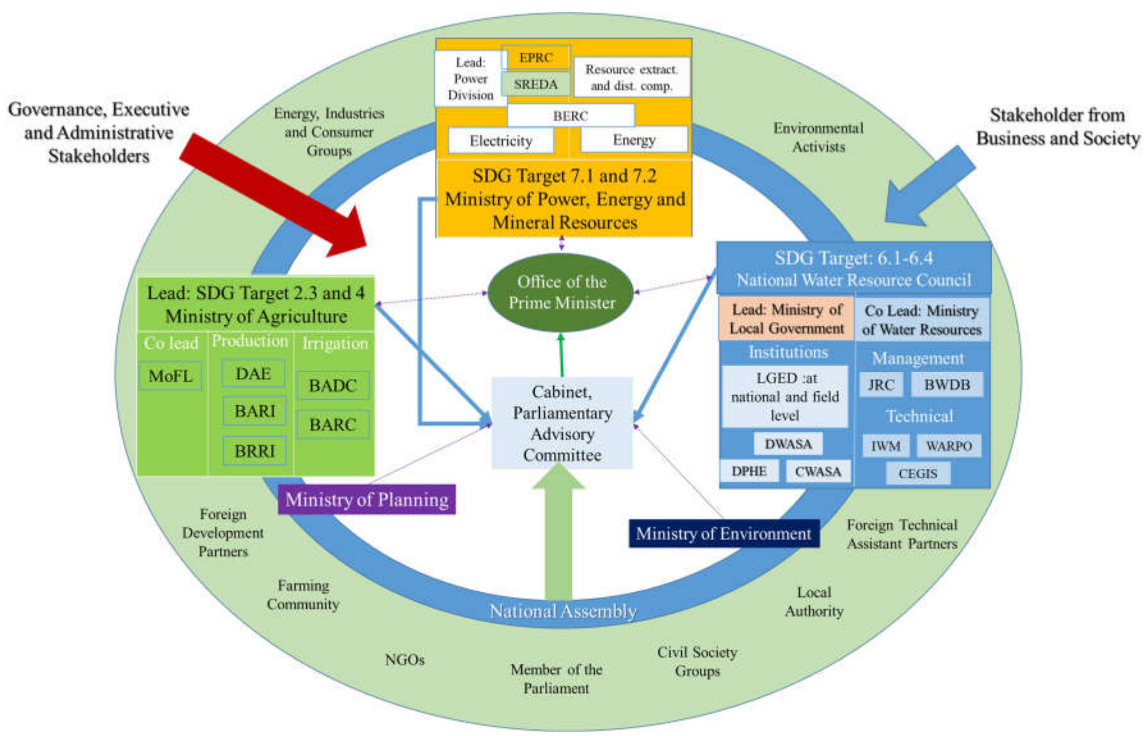

Figure 26: Conceptual stakeholder mapping of WEF core network and peripheral network.

In water resource management, National Water Resource Council (NWRC) is the apex body at national level, which is responsible for formulating policies, coordinating between agencies and passing policy recommendations to cabinet as well as coordinating management activities of water resources in the country. The expansion of irrigated areas, water body conservation, water use from reserves and river management are the executive responsibility for the Ministry of Water Resources (MoWR). Under national water policy 2018, it is in the duty of MoWR to formulate frameworks for institutional reforms to guide water related activities. Bangladesh Water Development Board (BWDB), under MoWR, performs responsibility including planning and executing water projects, from coastal protection, flood control, building embankments to irrigation and drainage. Under the Delta Plan Bangladesh 2100, this institution is also responsible for re-excavation and maintenance of channels, land reclamation and erosion control. Flood forecasting, research hydrological surveys, coordinating among other water stakeholders and associations are also within jurisdiction of this board. Joint River Commission (JRC), is the recommendation body for transboundary river management and water distribution in the country. Based on the recent environmental condition, too little water during dry seasons and more water during wet seasons have been pushing farmers to relay on underground water source then surface water. Maintaining sufficient river flows throughout the year by ensuring proper discharge in transboundary rivers can increase surface water availability for agriculture. Technical institutions, such as Institute of Water Modelling (IWM), deals with the mathematical modelling of water sources, Center of Environment and Geographic Information System (CEGIS) provides mathematical assistances whereas Water Resource Planning Organization (WARPO) is responsible for national water resource database and provide consultation on planning and projects on water resources (Gupta et al. 2005). The Local Government Division (LGD) and Local Government Engineering Division (LGED) of Ministry of Local Government, Rural Development and Cooperation (MoLGRDC) perform development and management of rural project, including flood control, irrigation (1000 ha or less), water supply and sanitation. It is the institution which is more involved with local communities and stakeholders. Department of Public Health Engineering (DPHE) is involved in development projects for safe water supply and sanitation in rural areas and peri municipal areas. Dhaka Water Supply and Sewerage Authority (DWASA) and Chattogram WASA are responsible for domestic, industrial and commercial water supply in Dhaka, the capital and Chattogram, the port city of Bangladesh. Planning treating waste water facilities for reuse also falls on these institutions, through LGRD.

Ministry of Power, Energy and Mineral Resources (MoPEMR) is the top institution for formulating policies and recommendation on primary and secondary energy management. It supports two streams of managements, one being electricity generation, transmission and distribution, Power Division (PD) and other being management of domestic extraction, processing and imported primary energy sources, the Energy and Mineral Resource Division (EMRD). Bangladesh Energy Regulatory Commission (BERC) looks over the pricing of energy in the country. Sustainable Renewable Energy Development Authority (SREDA) promotes and provides support to expand renewable energy. The

Power System Master Plan involves PD and SREDA in making long term planning for setting the future electricity infrastructure for Bangladesh. World Bank and Infrastructure Development Company Limited (IDCOL) works for expanding standalone solar home facilities in rural areas. All of the aforementioned ministries have to get an environmental clearance from Ministry of Environment and Forestry (MoEF) for any massive infrastructural planning. MoEF provides certification for environmental friendliness of any infrastructure and development work. Ministry of Land (MoL) is in charge of land zoning throughout the country to demarcate areas for agricultural and non-agricultural land use. Last but not least, Planning Division of Ministry of Planning (MoP) is responsible for formulating, coordinating development works and financial support among ministries. Fig. 26 also illustrates the schematic diagram for institutional framework for institutions involved as stakeholders from government. The PMO, national assembly, local authority and other interest groups can play also play vital roles on integrating policies and development. However, these actors can provide direction whereas the administrative and technical support mainly comes from government organization as well as other foreign donor and international development partners such as FAO, UN, WB, ADB, JICA and USAID. There are also other ministries and stakeholders involved in such interactive sphere, but for the sake of simplicity, the core institutions are mentioned here to conceptualize a working framework. Every proposal and infrastructure investment decisions are passed through, ECNEC, Executive Committee for National Economic Council and Cabinet for final approval, which also provides a ground for different ministries to interact before executing a plan. To

Table 16: Stakeholders involved in policy decision and planning

Resource: Water	
Decision	Institutions
Surface water availability and usage	MoA (BADC, BARC) MoFL(Fisheries and life beneath water) MoWR (BWDC) LGD (Water bodies up to 1000 ha) MoEF (Preservation) SREDA (Hydro power)
Ground water availability and usage	MoA (BADC, BARC) MoWR (BWDC) LGD
Treated waste water availability and usage	LGD PD (Availability of energy)
Resource: Food	
Agriculture: Production	MoA (DAE, BARI, BRRI) LGRD (Involvement with local communities for disseminating supplements and incentives in agriculture)
Agriculture: Irrigation	MoA (BADC, BARC) MoWR (BWDB) LGD
Resource: Energy	
Energy: Electricity	PD SREDA BWDB (Hydro power) MoA (Biomass and waste) LGD (Municipal waste) MoE (Controlling emission and pollution)
Energy: Primary Source	EMRD MoE (Controlling emission and pollution)

conceptualize how a scenario includes or involves different stakeholders inside government, it is crucial to know how, decisions regarding resource usage, production, conservation and managements are connected in the institutional framework. As the institutional involvement described above, the following table (table 16) summarizes key stakeholders in executing a policy decision based on the developed WEF network and peripheral network model.

Let us consider a hypothetical scenario to show how government institutions are connected, actively or passively, in making decisions. The hypothetical scenario involves a water portfolio of 50% surface water(SW), 45% ground water(GW) and 5% treated waste water(TWW) use for agriculture and energy, 85% self-sufficiency (%SS) in ten major crop production where 100% of total pulses, maize and sugarcane are produced locally with 10% of total generated electricity comes from biomass and waste (10% Renewable) and 30% nuclear power plant. Treated waste water facilities are currently under jurisdiction of LGD. So, based on the prevailing structure, using treated waste water for agriculture make BADC fully dependent on LGD. LGD has the power to interact with local stakeholders, i.e. crop producers for changing their cropping pattern which yields higher production volume and lowers the withdrawal of groundwater for irrigation. DAE can change the production pattern at root level to change the portfolio in national food basket. Setting more biogas and biomass plants in rural areas by SREDA, can reduce the stress on electricity generation from fossil fuel and impacts from emission by using huge agricultural waste produced in farming. Thus, strategic position of power plants can reduce the pressure on electricity demand (PD). It can also expand the opportunity of treated waste water in peri urban agriculture. However, there is evidence which showed using treated waste water (BADC, LGD) for crop production increases yield gap of crops, which might rise an opposition stand from DAE (Roy et al. 2013).

Thus, understanding of cross sectoral resource influence and resource balance can help such government institutions, as stakeholders, to express their views and concerns on a future plan that actively connects to resource and priority hotspots. In the next chapter, results for each scenario will be analyzed based on output and discussed on the basis of policy and stakeholder mapping shown in preliminary calculations. Only results which does not pose any physical resource constraints are to be checked against the mapping, where ministries and stakeholders have different objectives connected to resource hotspots.

5. SCENARIO ASSESSMENT WITH WEF NEXUS TOOL

Rather than searching for scenarios to be assessed randomly, it is prudent to start building scenarios from a point which stakeholders are more inclined to pursue. Ministry of agriculture, as a leading ministry in fulfilment of SDG 2, is more dedicated in attaining 100% self-sufficiency in food production whereas Power Division is more inclined to generate electricity from coal fired power plant. Ministry of Water resources and Local Government Division are in charge of sustainable water resource management irrespective of water sources. The base scenario is developed based on what individual ministries, working in silos, planned for future and all assessments based on the scenario input will serve as the base for comparison. As bio-physical resources are short in supply (land and water) and have temporal dependency (water availability and cropping pattern in dry and wet season), all assessments made from scenarios will be passed through the resource constraints filter. In addition, it is worthy of knowing, while fulfilling goals of one ministry, how much other ministries or government institutions have to sacrifice. For instance, how much land the agriculture sector has to give up in fulfillment of energy goals, or how much excess energy is required to make treated waste water available for agriculture can be realized by framing scenarios and examining assessments made for each scenario. As shown in fig 25, rather than moving at the extreme points of the scenario matrix, the trade-offs and synergies found in different scenario can be a starting point for decision makers for revisiting plans by acknowledging tight resources interactions. The

Table 17: Description of 7 different scenarios to be assessed

Input Portfolio	Scenarios						
	Base Scenario	1	2	3	4	5	6
Percentage of food production (%SS)	85% SS in major crops	100% Self Sufficiency for ten major crops	100% SS in Cereal (Rice and Maize) Others-BAU	85% SS in Rice 50% Jute Others BAU	80% Rice 22.5% Wheat 80% Maize, Pulses 50% Jute Others BAU	70% SS in Cereal (78% Rice and Maize) 50% Jute, 23% Wheat 100% SS in others	80% SS in Cereal 50% in Jute BAU in others
Percentage of share in energy mix	Coal 1.6% Gas 58.6% Oil 32% Import 4.74% Renewable 3.06%	Coal 55% Gas 15% Oil 4.5% Import 12.5% Nuclear 10% Renewable 3%	Coal 45% Gas 25% Oil 4.5% Import 12.5% Nuclear 10% Renewable 3%	Coal 35% Gas 35% Import 10% Oil 12% Nuclear 5% Renewable 3%	Coal 25% Gas 25% Solar 10% Hydro 5% Wind 5% Others BAU	Coal 25% Gas 25% Import 15% Nuclear 15% Renewable 10%	Coal 25% Gas 25% Import 15% Nuclear 10% Solar 10%
Water sources	GW 79% SW 21%	GW 79% SW 21%	GW 70% SW 30%	GW 65% SW 30% TWW 5%	GW55% SW 40% TWW 5%	GW 50% SW 45% TWW 5%	GW 45% SW 45% TWW 10%
Population growth 2030	0.8%	0.8%	0.8%	0.8%	0.8%	0.8%	0.6%
Population growth 2041	0.6%	0.6%	0.6%	0.6%	0.6%	0.6%	0.5%

*BAU= Business as usual for base year 2016 following table (table 17) shows 7 scenarios with base case scenario. The scenarios tabulated in table 17 have different dimensions. Scenario, as mentioned before, developed based on long term planning made by each ministry. For energy, the base case is selected based on energy mix of 2016. According to long term water resource management planning, Delta Plan 2100, the ministry of water resources is planning to build reserve for rainwater for irrigation. To see how much stress food and energy sector put on existing resources; the water portfolio is kept as same as base year 2016. To set the future food demand, the food requirement has been population adjusted for 2030 and 2041 according to the SSP2 (medium) population projection, which is around .8% from 2016 to 2030 and 0.6% from 2030 to 2041 (Lutz et al 2014). Rest of the scenarios are developed in order to search to what extent each silo goals, can with synergy or trade-off, boast or hinders other goals as well as how does those scenarios help in achieving SDGs and NPIs. **The base scenario** is defined as what if the decision makers keep doing what they were doing in 2016. The total self-sufficiency for ten major crops has been kept same as 2016 for year 2030 and 2041 respectively. The energy portfolio for electricity is kept as same as 2016, which is dominated by gas. The volume of electricity production projected for 2030 and 2041 is kept as same as national planning. The water portfolio does not contain any treated waste water share. The share in water portfolio is largely shared by ground water (79%). The energy input in agriculture has been assumed to be comprised of 50% fertilizer and pesticides are imported, thus not contributing in emission for food production. The annual land loss is kept 0%. These assumptions have been kept same for all scenarios.

If electricity plants are allowed to set on arable lands, it would reduce usable land for agricultural production by 3% in 2030 and 4% by 2041, The total land require for projected crop production, where demand is driven by the population growth predicted for 2030 and electricity generation projected by the national planning. The blue water stress has increased by 10% in 2030 and 16.4% by compared to the base year 2016.

Table 18: Base scenario for water, food and energy portfolio and model assessments

Input						Output		
Food (% SS)			Electricity (% in share of MW)					
Crop	2030	2041	Source	2030 (32000)	2041 (54000)	Assessments	2030	2041
Rice	94.6%	93%	Coal	1.60%	1.60%	Land (M ha)	9.02	9.38
Wheat	23%	22%	Oil	32.00%	32.00%	Water (BCM)	128	135
Potato	100%	100%	Gas	58.60%	58.60%	Food Import (%)	15%	15%
Jute	100%	100%	Biomass	0.00%	0.00%	Energy in Ag (TWh)	54.4	57.3
Maize	85%	85%	Import	4.74%	4.74%	Energy in TWW (TWh)	-	-
Pulses	100%	100%	Nuclear	0.00%	0.00%	% Renewable	3.1	3.1
Oil Seeds	100%	100%	Hydro	0.80%	0.50%	Carbon Footprint		
Spices	100%	100%	Solar	2.06%	2.36%	CO2 emission Ag(MT)	17	17.8
Sugar cane	60%	60%	Wind	0.20%	0.2%	CO2 emission elect.(MT)	91	155
Vegetables	100%	100%	Water resources by % share			Imported Energy for Agriculture		
				2030	2041		2030	2041
			Surface	21%	21%	Fertilizer	50%	50%
Population Growth 2030 0.8% Population Growth 2041 0.6%			Ground	79%	79%	Pesticide	50%	50%

The country is already withdrawing more ground water than its recharge capacity. The assessment indicates, if the country keeps allowing groundwater abstraction without regulation, it might face lowering of ground water level in near future. Crop production is

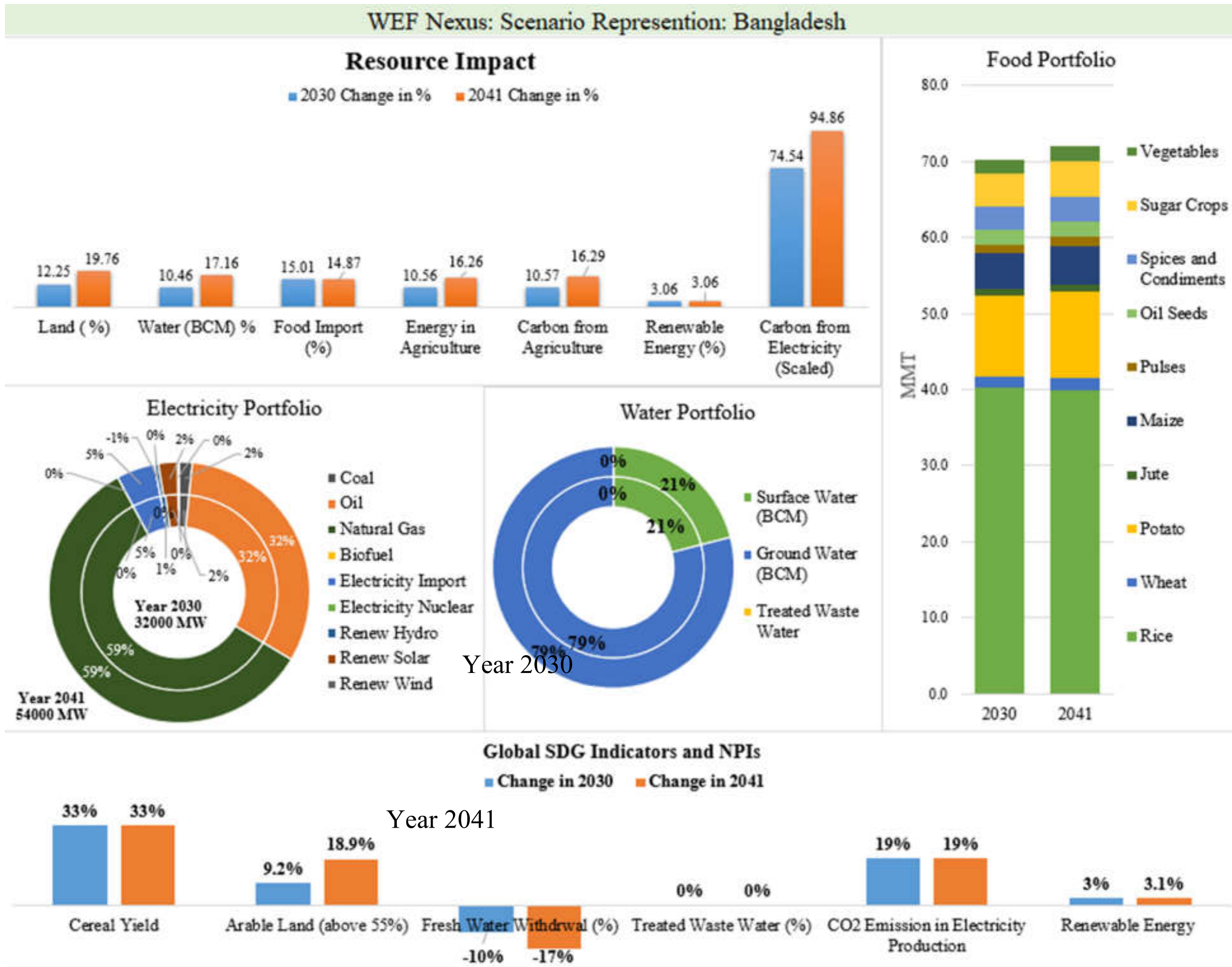

Figure 27: The output of the tool for base scenario.

responsible for the base stress on land (92% of the total land requirement) and water (99.3% of the total water requirement assessed) in 2030 and 2041 whereas electricity generation is the major contributor to carbon emission. The renewable energy portfolio is kept at same percentage (3.06%) as year 2016. If the emission is being taxed, say $40 per ton, the country has to pay nearly $4bn in 2030 and $6.32bn in 2041 as carbon tax in present value per year of operation compared to $40bn investment in power plant establishment. Table 18 tabulates the input portfolio for base scenario and fig. 27 shows the corresponding output in clusters. The changes in SDG indicators and NPIs compared to global indicator standards and national standards are also shown in the figure (negative

Table 19: Scenario 1 water, food and energy inputs and assessments

Input						Output		
Food (% SS)			Electricity (% in share of MW)					
Crop	2030	2041	Source	2030 (32000)	2041 (54000)	Assessments	2030	2041
Rice	100	100	Coal	55.00%	55.00%	Land (M ha)	11.12	11.93
Wheat	100	100	Oil	4.50%	4.50%	Water (BCM)	139	148
Potato	100	100	Gas	15.00%	15.00%	Food Import (%)	0%	0%
Jute	100	100	Biomass	0.00%	0.00%	Energy in Ag (TWh)	63.3	67.5
Maize	100	100	Import	12.50%	12.50%	Energy in TWW (TWh)	-	-
Pulses	100	100	Nuclear	10.00%	10.00%	% Renewable	3.0	3.0
Oil Seeds	100	100	Hydro	0.80%	0.80%	Carbon Footprint		
Spices	100	100	Solar	2.00%	2.00%	CO_2 emission Ag(MT)	19.61	20.94
Sugar cane	100	100	Wind	0.20%	0.20%	CO_2 emission Elect.(MT)	154.9	259.4
Vegetables	100	100	Water resources by % share			Imported Energy for Agriculture		
				2030	2041		2030	2041
			Surface	21%	21%	Fertilizer	50%	50%
Population Growth 2030 0.8% Population Growth 2041 0.6%			Ground	79%	79%	Pesticide	50%	50%

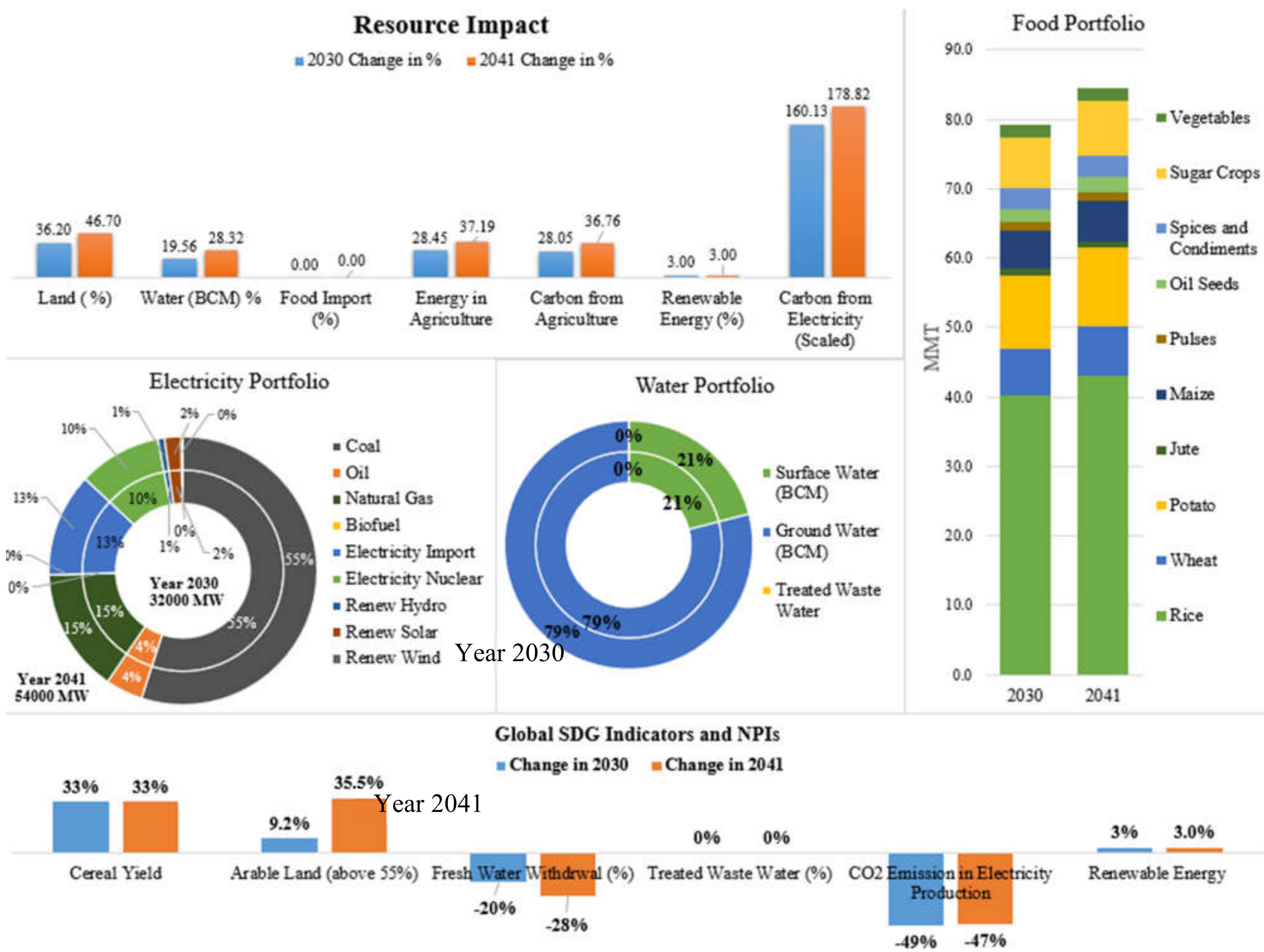

Figure 28: Assessment dashboard for scenario 1.

change implies away from and positive change implies in direction of standard). Only NPI 4 and SDG indicator 2.4.1 are achieved. Under these set of strategies, the country can keep 85% self-sufficiency in crop production up to year 2023. After year 2023, producing more crop will need more land and water than the national resource limit, excluding other sectors.

Scenario 1 is defined with a hypothetical self-sufficiency for all major crops in future for 2030 and 2041, considering the population growth remains moderate and the food consumption pattern remains as same as base year 2016. The energy portfolio kept as similar as scenario 1 mentioned in PSMP 2016 where the projected demand for electricity is 32000MW by 2030 and 54000 MW by 2041. The water portfolio consists of changing share in ground and surface water but no share for treated waste water. The volume of water demand is calculated based on input portfolio of food and energy. Table 19 shows the input and output for base scenario. Fig. 28 illustrates the overall assessments for base scenario. It is important to note that under base year 2016 resource flow characteristics, the arable land requirement exceeds the national arable land limit by 2.57 Mha in year 2030 and 3.4 Mha in year 2041, if annual land loss is kept 0%. Table 19 tabulates the input for the scenario 1 and the corresponding output. On the other hand, the water requirement increases by 21% and 30% compared to base year and crossing national renewable water reserve limit (105 BCM). The renewable integration drops down to 3% in 2030, whereas the emission from electricity production becomes 3 and 5 times higher than base year, which is mostly due to rise in production volume and % increase in share of coal. From the estimation, it can be seen that 100% food sufficiency is not achievable because of the excessive land requirement of land and water for agriculture. In terms of resource constraint, this scenario exceeds the available arable land limit and renewable water resource limit (shown in fig. 29). This food and energy centric scenario also fail in attaining one of the directly national priority, attaining 10% renewable energy. Electricity production yield more carbon emission per TWh for increasing coal share in the energy mix almost by 55%. From the assessments, it is conspicuous that attaining 100% self-sufficiency is not attainable whereas electricity generation introduces only a little stress, while agriculture sharing the base stress for land and water. The energy input to crop production is directly connected with the production volume and so does the emission

Table 20: Scenario 2 water, food and energy inputs and assessments

Input						Output		
Food (% SS in all crop)			Electricity(% in share of MW)					
Crop	2030	2041	Source	2030 (32000)	2041 (54000)	Assessments	2030	2041
Rice	100	100	Coal	45.0%	45.0%	Land (M ha)	9.48	10.21
Wheat	22	22	Oil	11.8%	11.8%	Water (BCM)	134.5	144.45
Potato	100	100	Gas	25.0%	25.0%	Food Import(%)	11.0%	10.2%
Jute	100	100	Biomass	0.0%	0.0%	Energy in Ag (TWh)	57.2	61.1
Maize	100	100	Import	10.0%	10.0%	Energy in TWW (TWh)	-	-
Pulses	100	100	Nuclear	5.0%	5.0%	% Renewable	3.0	3.0
Oil Seeds	100	100	Hydro	0.8%	0.5%	Carbon Footprint		
Spices	100	100	Solar	2.2%	2.6%	CO_2 emission Ag(MT)	17.8	19
Sugar cane	60	60	Wind	0.20%	0.12%	CO_2 emission Elect.(MT)	147	246.8
Vegetables	100	100	Water resources by % share			Imported Energy for Agriculture		
				2030	2041		2030	2041
			Surface	30%	30%	Fertilizer	50%	50%
Population Growth 2030 0.8% Population Growth 2041 0.6%			Ground	70%	70%	Pesticide	50%	50%

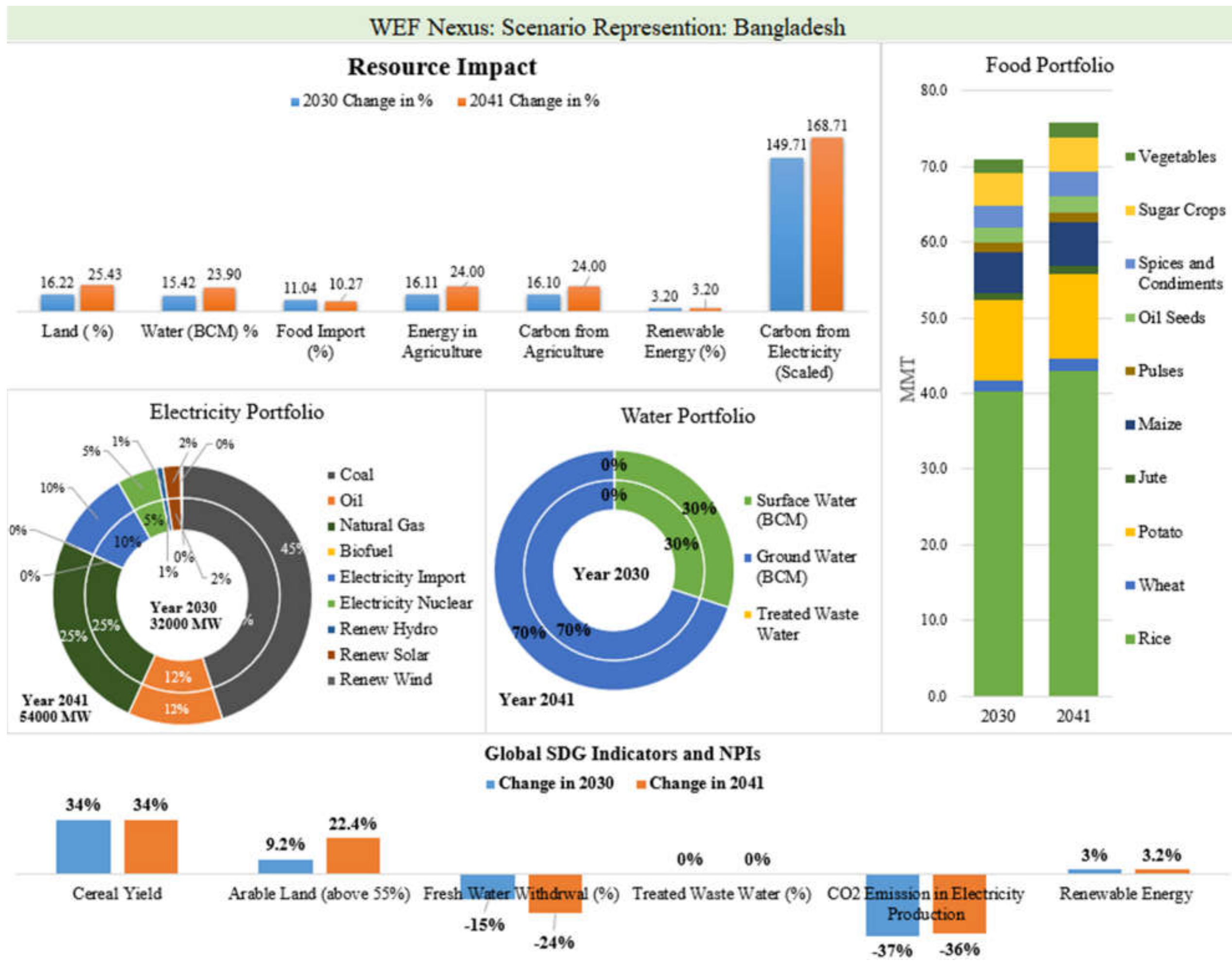

Figure 29: Assessment dashboard for scenario 2

from agricultural production. Under base scenario, treated waste water was not considered as an option for irrigation. This scenario demonstrates policies which are not seemingly contradicting with each other right now, might face resource constrains as moving forward in silos. The rest of the scenarios, as mentioned in the previous chapter, is based on searching for scenarios which fits stakeholders' interest with minimum stress on core and peripheral network. Based on the assessment of the scenario, it is clear that to reduce blue water stress, the share of different water sources is needed to be changed, whereas, the volume of the domestic food production has to be revisited.

Scenario 2 is developed to assess whether it is achievable if the ministry of agriculture wants of cereal self-sufficiency, which is by definition of FAO, contains major and minor cereal, while changing the energy dependency slightly from coal to gas. As the base scenario increased blue water stress, increasing share of surface water can shift the stress to surface water which is one of the core-development plans of DPB 2100. On the other hand, food production has a temporal and spatial variability, under which, attaining 100% self-sufficiency for a specific crop might not be doable as the land type required for such production is not available all around the country (Nasim et al 2017). The following table shows the input portfolio and output for scenario 2. All the assessed outputs are shown in dashboard figure 30. The self-sufficiency for wheat production is kept to base year value, while increasing %SS for rice and maize to 100% as the government is more inclined towards wheat import than domestic production (USDA, 2019).

All the assessments as well as corresponding SDG and national indicators are shown in fig. 30. The assessments show that attaining %SS in major cereals is not possible in long run under prevailing resource flow as it demands more land, lower than base scenario but 0.6 M ha above the arable land limit in spite of 13% import dependency. 9% increased share in surface water usage has reduced stress on ground water by 9%. However, increasing dependency on coal-based power generation by 45% which is similar to scenario 2 of PSMP 2016, has resulted in 10% increase in emission compared to base case. Due to reduction in production volume, the energy input and emission from agriculture sector are lower compared to base case.

Table 21: Scenario 3 water, food and energy portfolio and assessments

Input						Output		
Food (% SS)			Electricity (% in share of MW)					
Crop	2030	2041	Source	2030 (32000)	2041 (54000)	Assessments	2030	2041
Rice	85%	85%	Coal	35.00%	35%	Land (M ha)	8.53	9.19
Wheat	20%	20%	Oil	4.50%	4.50%	Water (BCM)	116	124
Potato	100%	100%	Gas	35.00%	35%	Food Import (%)	20.5	19.1
Jute	50%	50%	Biomass	0.00%	0.0%	Energy in Ag (TWh)	49.5	52.8
Maize	85%	85%	Import	10.00%	10%	Energy in TWW (TWh)	3.1	3.4
Pulses	100%	100%	Nuclear	10.00%	10%	% Renewable	5.5	5.5
Oil Seeds	100%	100%	Hydro	0.80%	0.80%	Carbon Footprint		
Spices	100%	100%	Solar	4.50%	4.50%	CO_2 emission Ag(MT)	15.4	16.4
Sugar cane	60%	60%	Wind	0.20%	0.20%	CO_2 emission Elect.(MT)	122	143.6
Vegetables	100%	100%	Water resources by % share			Imported Energy for Agriculture		
				2030	2041		2030	2041
			Surface	30%	30%	Fertilizer	50%	50%
Population Growth 2030 0.8%			Ground	65%	65%	Pesticide	50%	50%
Population Growth 2041 0.6%			TWW	5%	5%			

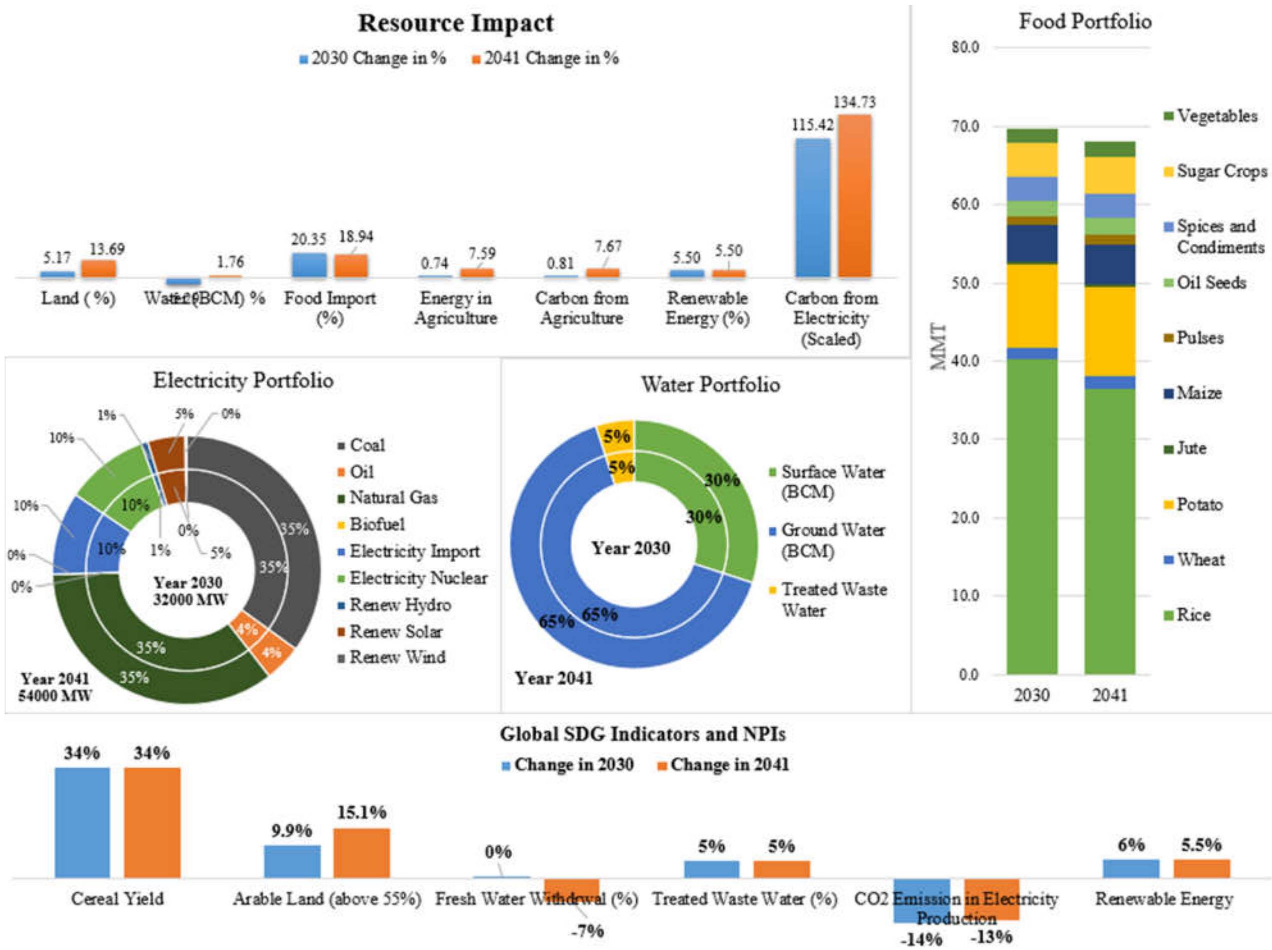

Figure 30: Assessment dashboard for scenario 3.

This scenario also falls under resource constraints of land with significant increase in emission from electricity generation. This scenario is not achievable even in 2016 as the country imports nearly 73% and 40% of its wheat and sugar demand respectively. To facilitate such high volume of wheat under low yield will require more land during winter when the country produces at least 40% of its rice. Under this scenario, only NPI 4 can be achieved.

Scenario 3 assumes the self-sufficiency similar as 2018 in major crops, where attaining 85% SS in rice production has been set. In this scenario, the share of surface water in total water demand for irrigation has been increased to reduce the pressure on ground water. The energy input required for TWW is almost 10% of total energy input in agriculture. Table 21 represents the input portfolio and outputs of scenario 3. Scenario 3, shows the first case which has passed the resource constraints by 2030, while reducing stress on land, water and emission, attained both NPIs and SDG indicators at the cost of increased dependency on import for food and energy. As the import % increased from 12% of scenario 2 to 21% in scenario 3 in year 2030, the stress on land, water and energy input for food production has been virtually shifted. 5% of the total water demand came from treated waste water under this scenario which has negligible impact on energy input and emission from domestic production. Introducing 5.5% renewable energy in total electricity generation, reduced the emission 16% compared to base scenario, with the additional demand for land. However, the scenario demands land more than the limit before 2041 for crop production. This strategy is not sustainable up to 2041 due to arable land and renewable water limit. Under this scenario, only NPI 4 and SDG global indicator for carbon emission from electricity generation is achievable both in 2030 and 2041. **Scenario 4** is more designed towards finding the extend of renewable energy that can be integrated. In this scenario, 20% renewable energy is introduced from various energy sources. A slight change in food portfolio is made by lowering self-sufficiency of rice and maize by 5% and 50% reduction in jute production. The share of ground water has been reduced to 55%, while letting the TWW be a source of water with 5% share. The input to scenario 4 and corresponding assessments are shown below in table 22 and fig. 31.

Table 22: Scenario 4 water, food and energy inputs and assessments

Input						Output		
Food (% SS in all crop)			Electricity (% in share of MW)					
Crop	2030	2041	Source	2030 (32000)	2041 (54000)	Assessments	2030	2041
Rice	80%	80%	Coal	25.0%	25%	Net Land (M ha)	7.8	8.54
Wheat	22.5%	22.5%	Oil	14%	14%	Water (BCM)	104	111
Potato	100%	100%	Gas	25.0%	25%	Food Import (%)	25%	23.3%
Jute	50%	50%	Biomass	0.0%	0.0%	Energy in Ag (TWh)	45.5	48.6
Maize	80%	80%	Import	11.0%	11.0%	Energy in TWW (TWh)	3.1	3.4
Pulses	80%	80%	Nuclear	5.0%	5.0%	% Renewable	20	20
Oil Seeds	50%	50%	Hydro	5%	5%	Carbon Footprint		
Spices	100%	100%	Solar	10%	10%	CO_2 emission Ag(MT)	14.17	15.13
Sugar cane	60%	60%	Wind	5.00%	5.0%	CO_2 emission Elect.(MT)	98.8	120.9
Vegetables	100%	100%	Water resources by % share					
				2030	2041	Imported Energy for Agriculture		
			Surface	40%	40%		2030	2041
Population Growth 2030 0.8%			Ground	55%	55%	Fertilizer	50%	50%
Population Growth 2041 0.6%			TWW	5%	5%	Pesticide	50%	50%

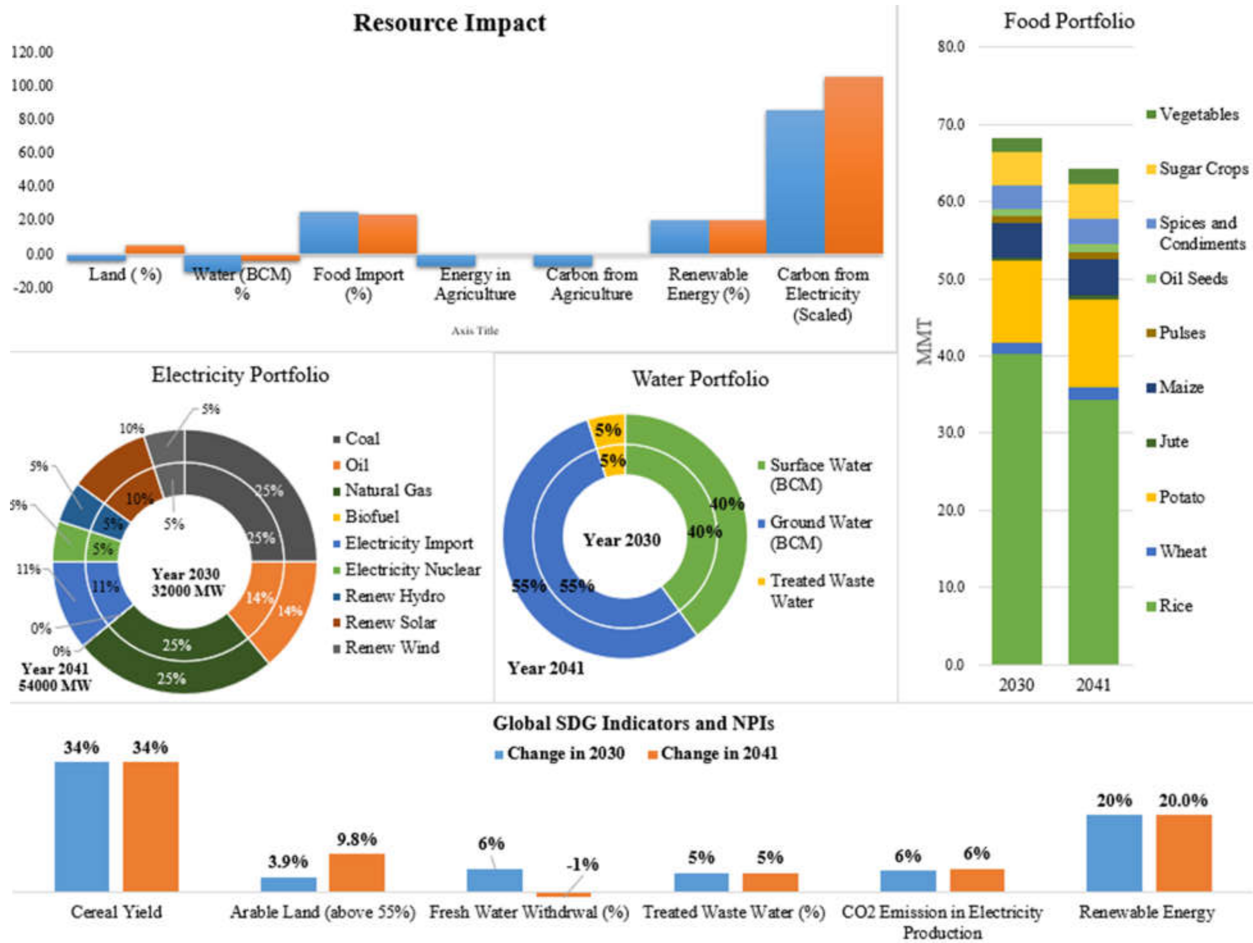

Figure 31: Assessment dashboard for scenario 4.

Scenario 4 is the perfect representation of the land for energy and food contention. Reducing self-sufficiency in food production by giving away land to renewable integration in electricity production has reduced the emission from energy production significantly with the cost of arable land. Reducing 5% self-sufficiency in rice and maize has also raised the food import, hence lowering energy input in agriculture. Treated waste water has alleviated pressure on ground water, reducing blue water stress below 100% with increasing need in electricity for agriculture.

Scenario 4 has also achieved NPI 4 and 20 with global SDG indicators for SDG 2, 6 and 7 in 2030. However, land stress from electricity generation becomes minimum if all of the renewable energy comes from solar power. This strategy also demands more land and water than national resource limit.

Scenario 5 is a shift of food portfolio from cereal self-sufficiency to other major crops. In this case, 100% for vegetables, sugarcane, spices, pulses and oil seeds are considered. The renewable electricity share has been kept to 10%, while the share of nuclear and imported electricity has increased to 10% and 15% respectively. Water resource share has been further reduced for ground water. The scenario sufficiently captures NPI 4 and 20, as well as global SDG indicators for SDG 2, 6 and 7 for both 2030 and 2041. The tabulated input and assessment results are shown in table 23 and fig. 32 respectively. From scenario 3-5, it has been seen that, there lies a trade-off between energy and food production, As Bangladesh has been using its arable land limit to its threshold for agricultural production, renewable integration is pushing agriculture for the marginal land that it has left. On the other hand, same scenario for 2030 might seem feasible but faces production, but the diet

Table 23: Scenario 5 water, food and energy inputs and assessments

Input						Output		
Food (% SS in all crop)			Electricity (% in share of MW)					
Crop	2030	2041	Source	2030 (32000)	2041 (54000)	Assessments	2030	2041
Rice	70%	70%	Coal	25.0%	25%	Net Land (M ha)	7.9	8.54
Wheat	23%	23%	Oil	14.2%	14.5%	Water (BCM)	94	100
Potato	100%	100%	Gas	25.0%	25%	Food Import (%)	25.6%	24%
Jute	50%	50%	Biomass	0.0%	0.0%	Energy in Ag (TWh)	42.5	27.1
Maize	70%	70%	Import	15.0%	15.0%	Energy in TWW (TWh)	2.9	3.2
Pulses	100%	100%	Nuclear	10.0%	10.0%	% Renewable	10.8	10.5
Oil Seeds	100%	100%	Hydro	.8%	.5%	Carbon Footprint		
Spices	100%	100%	Solar	5%	5%	CO_2 emission Ag(MT)	13.2	14.12
Sugar cane	100%	100%	Wind	5%	5%	CO_2 emission Elect.(MT)	100.4	168.4
Vegetables	100%	100%	Water resources by % share					
				2030	2041	Imported Energy for Agriculture		
			Surface	45%	45%		2030	2041
Population Growth 2030 0.8%			Ground	50%	50%	Fertilizer	50%	50%
Population Growth 2041 0.6%			TWW	5%	5%	Pesticide	50%	50%

resource constrains in long run 2041. Another important issue to be looked out for is the priority for crops. Historically, Bangladesh has utilized much of its land for rice pattern is shifting and it might influence the change in demand for different crops in future. Growing more food and producing cleaner energy are seemed to be working against each other, although cleaner energy reduces stress on water and environment. As the population will keep increasing in long run, the volume of food will also be in rise.

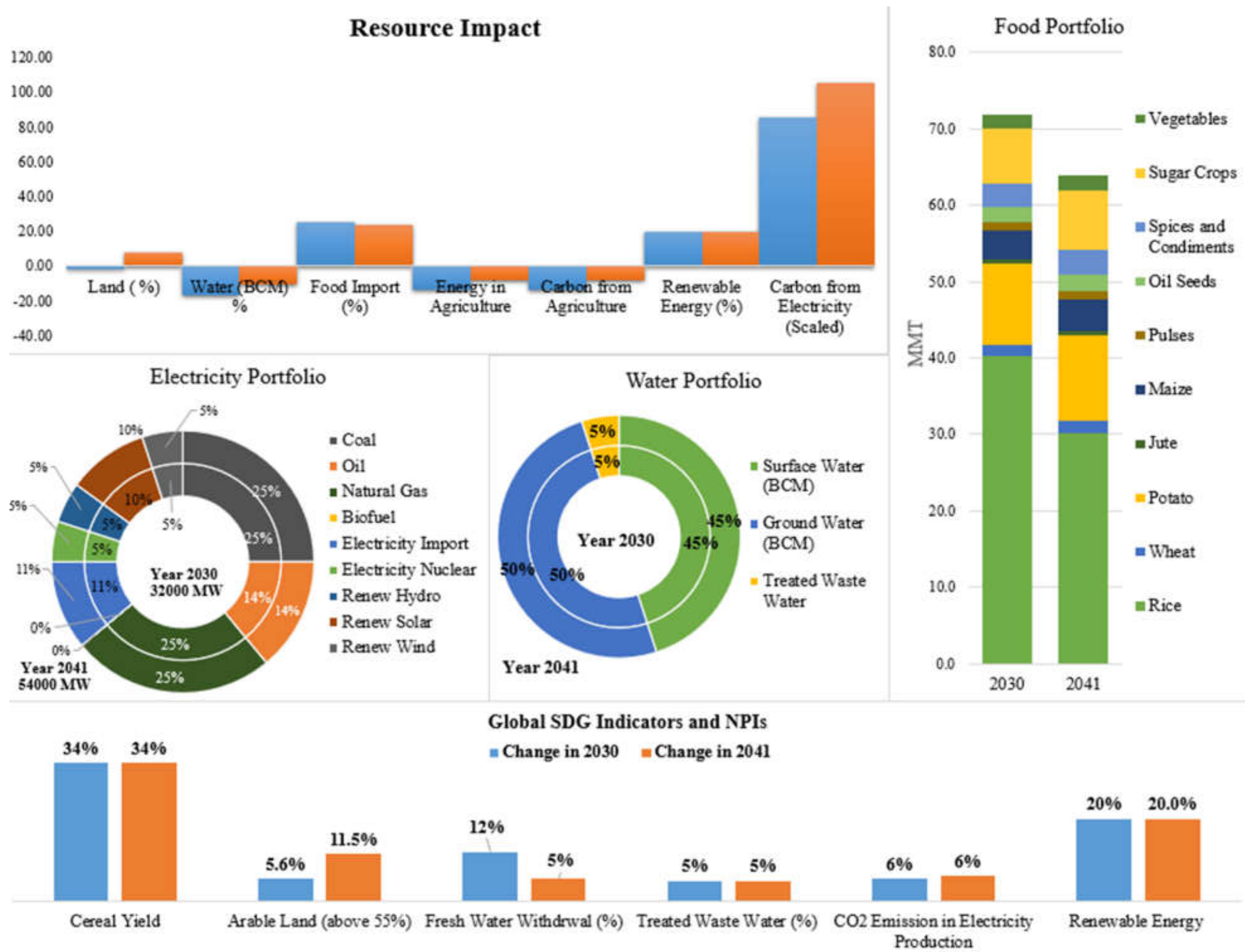

Figure 32: Assessment dashboard for scenario 5.

Table 24: Scenario 6 water, food and energy portfolio and assessments

Input						Output		
Food (% SS in all crop)			Electricity (% in share of MW)					
Crop	2030	2041	Source	2030 (32000)	2041 (54000)	Assessments	2030	2041
Rice	82%	82%	Coal	25.0%	25.0%	Land (M ha)	8.43	8.55
Wheat	22.5%	22.5%	Oil	14.2%	14.2%	Water (BCM)	100	105
Potato	100%	100%	Gas	25.0%	25.0%	Food Import (%)	19.2%	19.6%
Jute	50%	50%	Biomass	0.0%	0.0%	Energy in Ag (TWh)	48	49.6
Maize	100%	100%	Import	15.0%	15.0%	Energy in TWW (TWh)	6.4	6.8
Pulses	100%	100%	Nuclear	10.0%	10.0%	% Renewable	10.8	10.8
Oil Seeds	100%	100%	Hydro	0.8%	0.5%	Carbon Footprint		
Spices	100%	100%	Solar	10%	10%	CO_2 emission Ag(MT)	15	15.4
Sugar cane	60%	60%	Wind	0%	0%	CO_2 emission elect.(MT)	100	168
Vegetables	100%	100%	Water resources by % share					
				2030	2041	Imported Energy for Agriculture		
			Surface	45%	45%		2030	2041
Population Growth 2030 0.6%			Ground	45%	45%	Fertilizer	50%	50%
Population Growth 2041 0.5%			TWW	10%	10%	Pesticide	50%	50%

Scenario 6 is a bit optimistic, where the population growth has been kept slightly lower around 0.6% to see how does it stresses the resources. The electricity portfolio has been kept cleaner and the food portfolio is essentially same as scenario 3. The surface water resource is made the dominant water provider with 10% coming from TWW. Table 24 summarizes the scenario input and assessment whereas fig. 33 (in page 118) shows the assessment dashboard of the scenario. Scenario 6 has the volume of crop production is essentially same as base year 2016, the excess demand due to population growth contributes to the gross import of food. The energy mix for electricity is cleaner than scenario 1-4 with marginal pressure on land and water. Emission from agriculture has increased slightly because of increasing treated waste water availability for agriculture

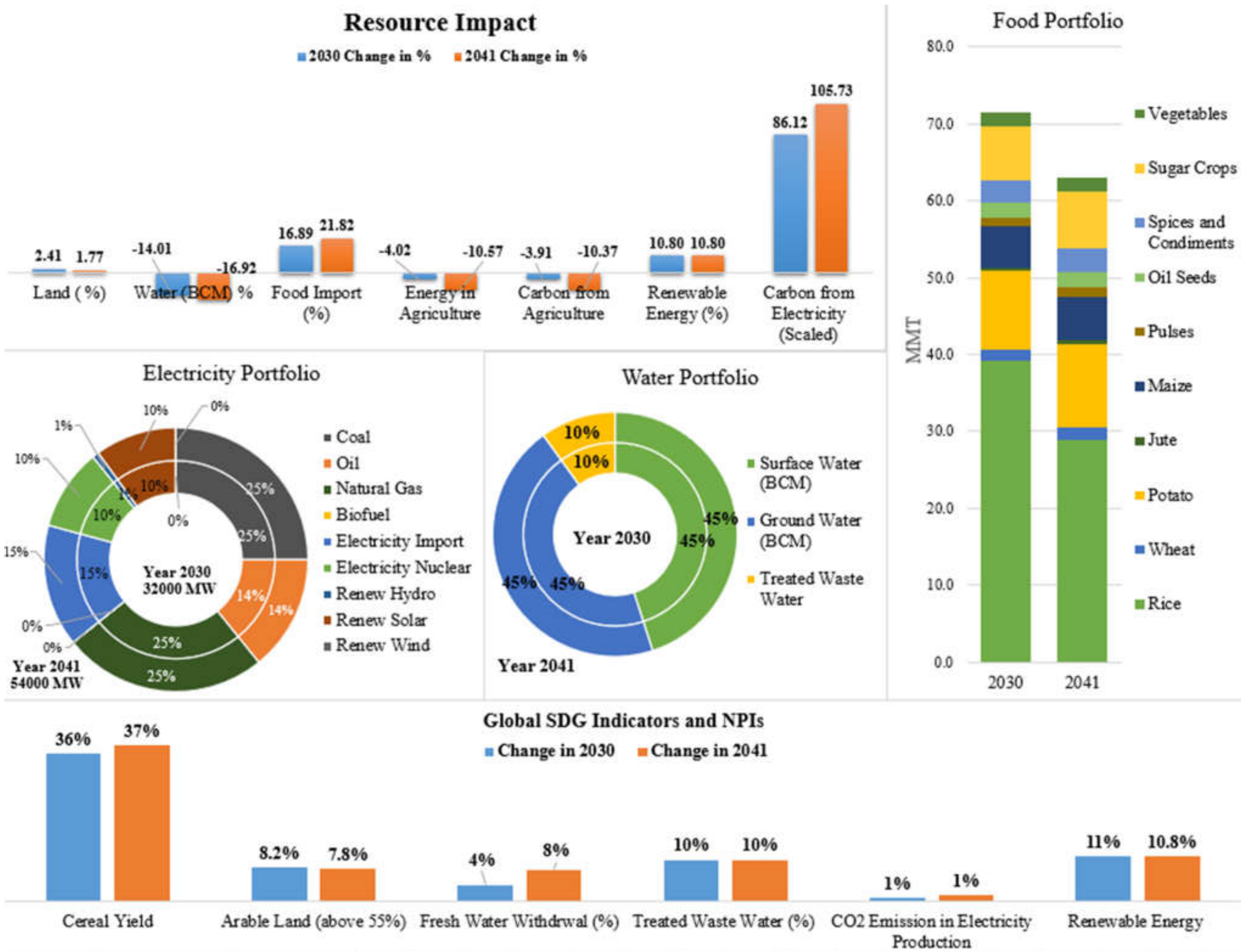

Figure 33: Assessment dashboard for scenario 6.

The electricity demand for treating waste water is almost double compared to other scenarios. Both of the NPIs and global SDG indicator for SDG 2, 6 and 7 can be addressed by scenario 6.

From all the scenario described above, there are no such cases when one of the targets could have achieved without acknowledging the resource requirement for other activity. Fig 34 shows the comparative assessments. All these scenarios are quantitatively summarized below, from resource perspective:

Land is the most sensitive of all resources. In graph (a) of fig. 34, the land required for agriculture and electricity production is shown in total for different scenario. The national arable land limit for Bangladesh is 8.6 M ha. Attaining self-sufficiency is not possible even if all the arable land is kept reserved for agriculture by 2030 and 2041 under moderate population growth. It is also worthy of pointing out that increasing population will demand land for settlement, commutation and commerce. Out of all the crop group, rice cultivation is prominent its cropping intensity and yield are higher compared to other crop in Bangladesh. Thus, reducing %SS on rice can be covered only by a limited number of crops in the cereal group, such as maize. From scenario 1-4, it is seen that the land given up by reducing %SS of different crops, is enough for 2030 but not 2041, which means that SS% of crop production has to decrease if the land demand from other sectors keeps increasing.

Again, there lies a competition between cash crop and food. Under increasing demand, it is a matter of decision which crop the country is willing to give up to attain self-sufficiency in which crop. For any of the energy mix in the energy portfolio, land requirement for electricity, production, transmission and distribution, only takes 5% of the total land used for agriculture under all scenarios which is found maximum for scenario 4 and 5, around 35 k Ha in total.

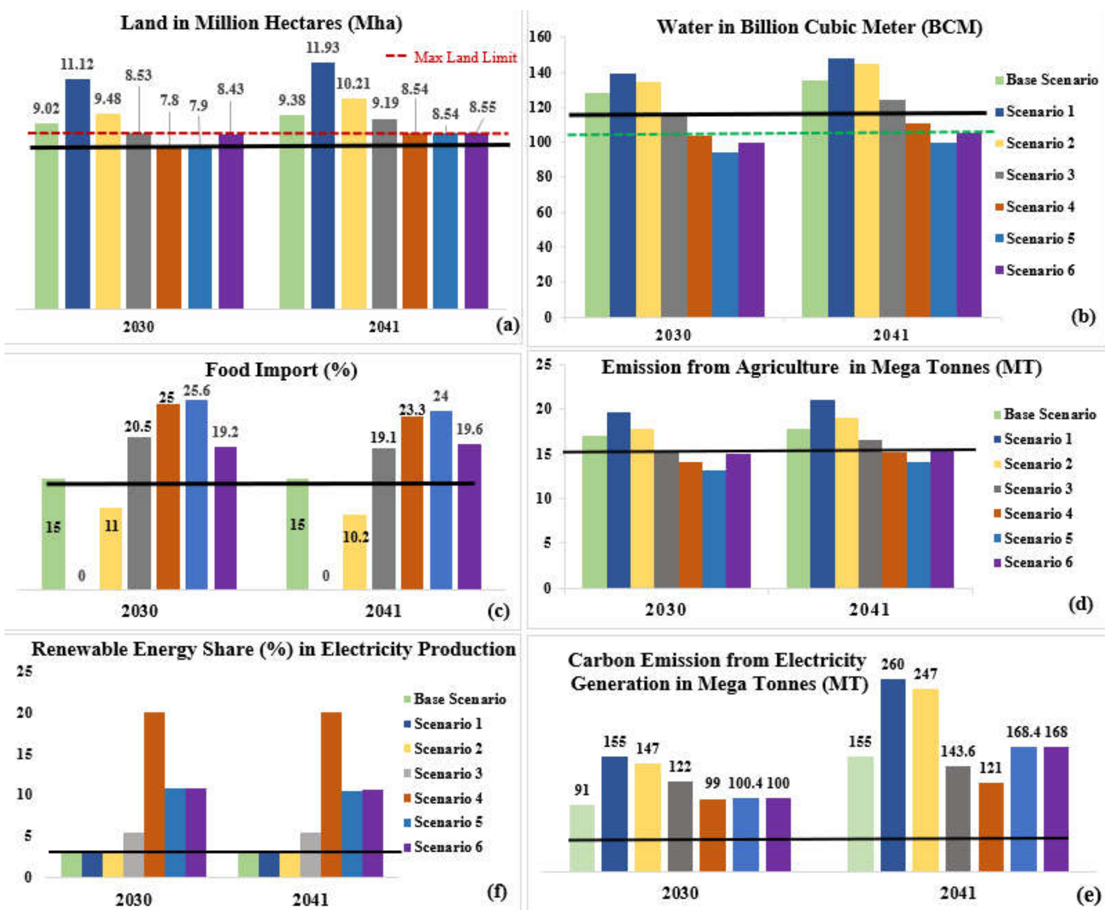

Figure 34: Comparative representation of assessments from base scenario to scenario 6. Red spaced line in graph(a) shows the national arable land limit whereas dark lines in all graph indicates the base year assessments. In graph (b), green spaced line indicates the national renewable water reserve capacity of Bangladesh

Under any scenario, competition for land between agriculture and electricity generation is not significant from agriculture perspective, but crucial from energy perspective as it facilitates more renewable integration. On the other hand, there is a spatial consideration for renewable electricity generation, such as solar electricity generation can be distributed, thus not necessarily colliding with food for land.

Land as a resource has been found more influenced by the change in %SS of crops rather than energy generation option. Cereals are the most land demanding crops, thus through the linear relationship showed in equation 4-15. In reality, such linear relationship is hard to find and depends on weather of each year (drought or rainy seasons). For different food portfolio, it is seen that shifting from cereal self-sufficiency to non-cereal food sufficiency, at a linear relationship is possible, shown in scenario 3 and 5, in both 2030 and 2041. This can be an indication for concerned ministries to revisit their priorities crop based self-sufficiency for long run. In fact, SDG target 2.3 (agriculture production efficiency) and target 6.4 (water use efficiency) can be revisited through estimating the price of production and compare under which case, the level of efficiency is more.

From scenario 1-6, it is conspicuous that land is the most sensitive of all the resources in the model as land use has already been using near threshold (Fig. 34 (a) and (c)). But, following the trend of population growth, the demand will keep rising, while land use will keep getting closer to facilitate all activities including food production. So, the food import will keep growing and concerned ministries should find ways to tackle the growing demand either by searching for high yield crop varieties or substituting low yield crops (jute, spices, pulses) with high yield crops (potatoes, sugar canes, vegetables, maize).

Surface water sources have remained unutilized. The water demand for food production runs the base stress on water. In case of cereal production, water productivity is much lower than other crops. Higher volume in cereal production demands more water. The water demand from electricity is lesser than 50 times to agricultural requirement whereas the consumptive water demand under all scenarios, are found closer to or exceeding the national renewable water reserve limit. To inspect, how impactful the demand is on different sources of water, it is found that the underground water is severely stressed compared to surface water. As assessment on scenarios moved from 1-6, the pressure on ground water has been reduced from 79% to 45% (Fig. 34(c)). Only at 45% share, the ground water stress (SDG Indicator 6.4.2) is found closer to the base year 2016. The share of water has been shifted to surface and treated waste water. Even if the share from surface water is increased to 100%, it is capable to support almost all the water demand from energy and food. But surface water has spatial diversity. Infrastructure are required to build to ensure availability of surface water for irrigation. The impact of treated waste water for agriculture has both sides, it reduces stress on existing water resources while consuming energy and raising emission. If 5% of total water comes from TWW, it reduces the stress on ground water at a cost of 10% increase in energy consumption and 5% increase in emission. From all the scenarios, it can be said that water portfolio should be directed more towards surface water resources to reduce pressure on ground water.

TWW facilities can be introduced where both surface and ground water have limited reserve capacity, mostly in urban and peri urban area. From all the cases mentioned above, the stress on water use is highly dependent on distribution. If the delivery from different water sources are evenly shared, the stress on single source can be reduced.

Emission from electricity generation will increase significantly based on fuel choice. For all the scenarios, changing the share of electricity generation from fossil fuel dominated to 20% renewable mix, the significant differences are seen in emission. For renewable integration up to 10%, the emission was reduced to 24% in 2030 and 20% in 2041 coupled with 15% electricity import from neighboring countries. Depending on coal-based power plant is a more emission intensive energy choice. If energy portfolio of scenario 2 is considered, the carbon tax for 2041 will be $7bn in present value ($40 carbon tax per tonnes). Bangladesh has voluntarily pledged to cut down its emission by 5% within 2030 to United Nations Framework Convention on Climate Change (UNFCCC), but under all of these scenarios, keeping the commitment, is not possible. On the hand, under base case scenario, the country will remain in achieving its national priority to attain 10% renewable energy integration in electricity mix. Fig. 34(f) shows the comparative renewable share for each scenario, whereas, fig. 34(e) shows the net emission from energy generation under each scenario.

Energy input and emission from agriculture is more volume dependent. As the model assumes that the local characteristics for food production will remain same, the energy input to food production and emission are dependent on two issues: 1) Production quantity of each crop and 2) sources of water. The model assumes that apart from energy input for irrigation, using water from treated waste water facilities will increase the energy input and emission in food production. Whereas, importing food can make those burden virtual, resulting in reduction of domestic energy demand and emission from agriculture. The comparative emission from agriculture for scenario 1-6 have been presented in fig. 34(f). The table 24 in the next chapter shows the evaluation of all the scenarios in terms of resource constraints (filter 1 of the 3-filter framework), national priorities (in terms of different ministries as stakeholder and NPIs) and SDG indicators.

6. DISCUSSION

At the beginning of the study, it was hypothesized that the absence of in-depth knowledge of decision makers in local water, energy and food sub-system interactions in national priority planning can increase the resource stress. To prove it, the policy priorities are screened, which showed that water and energy related policies have priorities than agriculture policies at present. Then, the system of the local water, energy and food sub-systems is being defined and key cross-sectoral interactions are being identified. A WEF assessment tool is developed to assess the outcome of a strategies, i.e. scenario. The tool facilitated a common platform for comparative assessment of different scenarios where the assessment parameters are set to reflect resource requirement and national priorities. The WEF assessment tool shows that the base demand for land and water comes from food production. As the food demand increase in future, the requirement for limited resources such as land and water keep increasing. Land use and water is also dependent on selection of crops. As the country is currently using more than 95% of its arable land for agriculture, setting more power plants will require more land, thus the trade-off lies in prioritizing energy over food production. Based on the local resource requirement the tool showed fossil fuel-based energy generation can be preferable in limiting the land use for electricity generation, compared to cleaner (nuclear) or renewable energy sources at the cost of emission. According to the assessments, 10% renewable energy integration in national electricity generation can reduce domestic production of crops up to 5%. This trade-off is avoidable if the power plants are built in arid or non-agricultural land.

Table 25: Screening all scenarios against resource constraints, national priority and SDG indicators to stakeholders

Scenario	Year	Physical Constraints		NPIs and Concerned Ministries		SDG Targets and Concerned Ministries					
				MoA	PD and	MoA	MoA	MoWR LGD	MoWR LGD	PD and MoEF	PD and
		Land	Water	NPI 4	NPI 20	Cereal Yield	% Area for agriculture	Fresh Water Withdrawal	TWW % (>50%)	Emission from electricity	Renewable mix (>10%)
Base Scenario 85% SS in crops	2030	×	×	√	×	√	√	×	×	×	×
	2041	×	×	√	×	√	√	×	×	×	×
Scenario 1 100% SS in crops, 55% Coal	2030	×	×	√	×	√	√	×	×	×	×
	2041	×	×	√	×	√	√	×	×	×	×
Scenario 2 100% SS in Cereal, 45% Coal ,30% SW	2030	×	×	√	×	√	√	×	×	×	×
	2041	×	×	√	×	√	√	×	×	×	×
Scenario 3 85% SS in Rice, 5% Renewable, 30%SW	2030	√	√	√	√	√	√	×	×	×	√
	2041	×	×	√	√	√	√	×	×	×	√
Scenario 4 80% SS in Cereal, 20% Renewable, 5%	2030	√	√	√	√	√	√	√	×	√	√
	2041	×	×	√	√	√	√	×	×	√	√
Scenario 5 70% SS in Cereal, 10% Renewable, 5%	2030	√	√	√	√	√	√	√	×	√	√
	2041	√	√	√	√	√	√	√	×	√	√
Scenario 6 80% SS in Cereal, 10% Renewable,	2030	√	√	√	√	√	√	√	×	√	√
	2041	√	√	√	√	√	√	√	×	√	√

MoA= Ministry of Agriculture, PD= Power Division, SREDA= Sustainable and Renewable Energy Development Authority, MoWR= Ministry of Water Resources, LGRD= Local Government Division, MoEF= Ministry of Environment and Forest

Significant trade-off lies in emission while choosing energy sources for electricity generation compared to water usage. The consumptive water use for any mix of energy sources are less than 1% compared to food, whereas the emission can be reduced as much as 30% for 10% renewable energy integration. Moreover, groundwater stress keeps on growing due to increased dependency. The demand for water is needed to be diverse. The surface water sources can reduce stress on ground water, but it demands investment on infrastructure development which is out of the scope for the developed tool. Treated waste water facility can also reduce pressure on ground water but it requires more energy and such establishment can add to emission. Even if we consider the highest energy consuming facility for water treatment, the assessment shows that the energy required for sharing 5% of total water demand is 13% of the total electricity generated with added 1 million ton annual carbon emission. Diversifying water sources are synergic to reduce ground water stress but imposes distinct level of trade-offs based on alternative source selection. More importantly, trade-offs become apparent where the resource is limited. The base scenario assessment showed that neither food self-sufficiency nor increased renewable energy integrations are achievable as there is only a little arable land left to use. Under this scenario, the ground water stress will be increasing causing resource depletion in future.

Thus, the base scenario, developed on existing policies and planning neither can achieve all national priorities nor reduce resource stress. Fig. 35 illustrates how each choice in a scenario can affect resource flows.

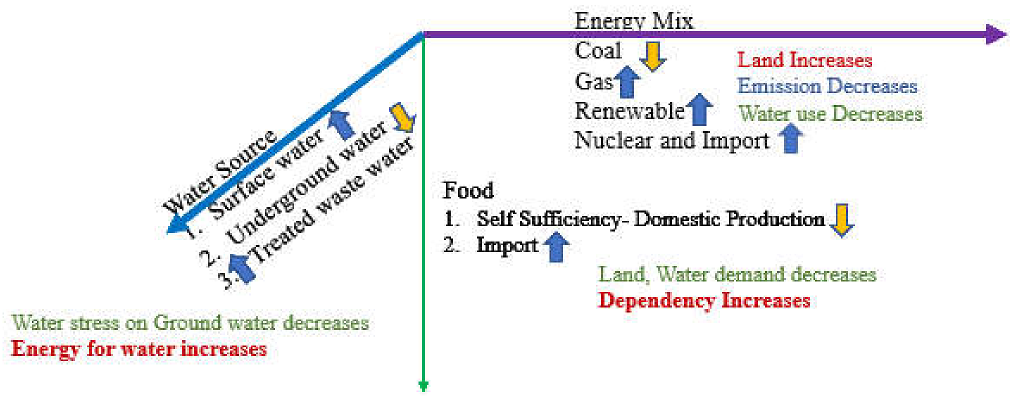

Figure 35: The impacts on resource flow while moving in a direction, summarized in a conceptual coordinate system.

Then a set of scenarios is built with single and overlapping interests, food self-sufficiency with more or less water share from ground water sources, electricity generation variation with food self-sufficiency, reducing pressure on water sources by introducing treated waste water and reducing the demand itself. Scenario 1-3 have served as evidence that little coordinated long term planning is undoubtedly stressing the resources where attaining only a few of the development indicators. On the other hand, multi-directional planning, have resulted in attaining more development indicator and national priorities with less stress on national resources showed in scenario 4-6. Although the assessment made here might be subjected to question to changing externalities, the tool and model can be revised to adopt such externalities and again assess scenarios to project the future resource requirements and hotspots.

When these scenarios were traced back to different ministries of Bangladesh showed in table 25, it is seen that implementation of such scenario involves coordination among all the connected ministries and institutes which are in position of governing resources and fulfilling national priorities as well as SDG targets, rather than prioritizing a handful of ministries. Better understanding in resource dynamics through

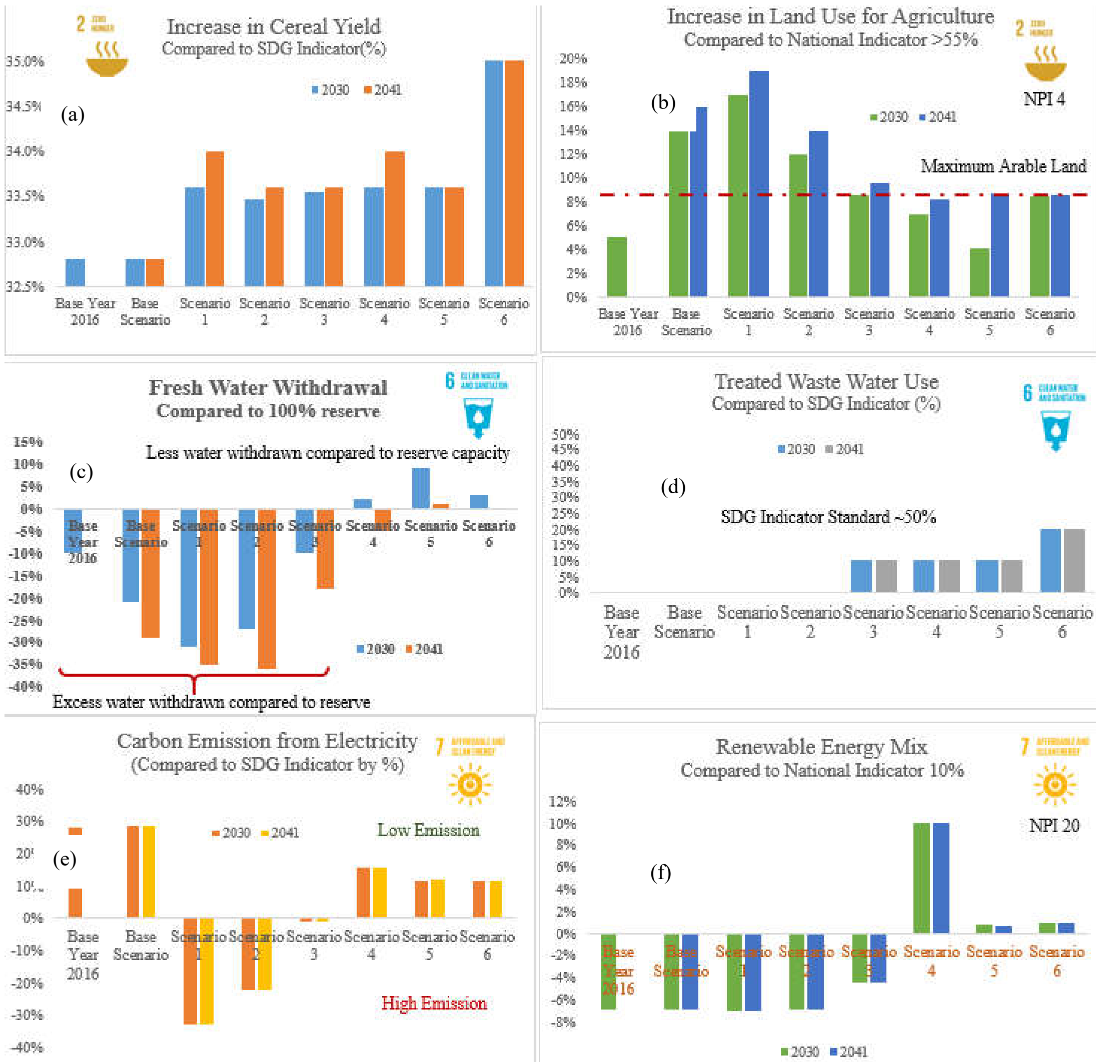

Figure 36: Comparative representation of the indicators assessed from each of the scenarios.

WEF nexus approach can help in attaining national priorities with reduced resource stress in future. But such representation lacks the representation of true achievements towards these indicators. The following figure illustrates how each scenario is approaching towards or away from the indicator standards. According to the global SDG standard, cereal yield is an indicator for reducing hunger, which falls in SDG 2. For base year, the self-sufficiency for rice and maize were 94% and 85% respectively. From the developed scenarios, it has been seen that scenarios with higher maize share in food self-sufficiency projects better cereal yield. Scenario 6 shows highest yield for 100% self-sufficiency in maize compared to 82% self-sufficiency in rice. For other scenarios, the self-sufficiency for both of the major cereals were kept same. The cereal yield for rice and cereal are around 3.1 t/ha and 8.25 t/ha respectively, whereas, the share of maize and rice in total cereal demand are 12% and 88% respectively. For scenario 6, the ratio was increased to 18% and 82% which resulted in slight increase in overall cereal yield (fig: 36(a)). However, the self-sufficiency projected for each scenario requires different amount of agricultural land. In base year 2016, nearly 82% of the total arable land and 60% of the total land had been brought under crop production. If Bangladesh wants to keep the same self-sufficiency, it will run out of arable land by 2021 under same productivity of major crops. Scenario 1, 2 and 3 are not possible to attain by 2030 either where self-sufficiency in food are projected more than 80%, because of the increased land and water requirement to sustain such production (fig. 36(b-c)). For self-sufficiency around 78%, projected in scenario 4, 5 and 6, the land requirement falls below maximum arable land in Bangladesh. Still the land requirements for these scenarios, shown in fig. 36(b) are well over the national priority indicator 4, connected to SDG 2 (arable land > 55% of total land). The unstainable water usage had already resulted in 10% more water withdrawal for agricultural production and energy processing in 2016 (fig. 36(c)). The water requirement for all the assessed scenarios were compared against the internal renewable water resources. As scenarios 1, 2, 3 including base scenario are crop production intensive, the associated water demand exceeds the total water reserve by as high as 35% (fig. 36(c)), whereas one of the SDG 6 global indicators for fresh water withdrawal is below 25% of the reserve. Unless treated waste water is introduced, scenario 4, 5 and 6 require more water than the reserve. For these scenarios, 5%-10% treated waste water can reduce the pressure on surface and ground water sources, compared to the global standard for 50% treated waste water use (fig. 36(d)). Carbon emission from electricity production is considered as one of the global indicators for SDG 7. The global average for carbon emission from per kWh electricity production is 475g. The carbon emission in electricity production for base year is calculated to be 360g, well below the global average, due to natural gas intensive electricity production. So, the base scenario, which assumes the same energy mix of base year 2016, is more a low emission energy mix for electricity production, compared to global average. However, coal intensive energy mix for scenario 1-2 are more emission intensive, 30% higher than present global average (fig. 36(e)). In latter scenarios, incorporating 5-20% renewable energy in total electricity production resulted in reducing carbon emission by 10-20%. Increasing renewable share by 10% in total electricity production is also a national priority connected to SDG 7. In fig. 36(f), the renewable energy share in different scenarios are shown. If fig. 36(e) and (f) are compared, strategies with less coal intensive and more renewable energy share (scenario 4-6) are lower in emission which can help the country in attaining global standard for emission as well as national priority of >10% renewable energy share in electricity production. The fig. 37 shows a temporal representation for each of the scenarios. Under limited resource constrains, an additional analysis is being performed to assess, how long each

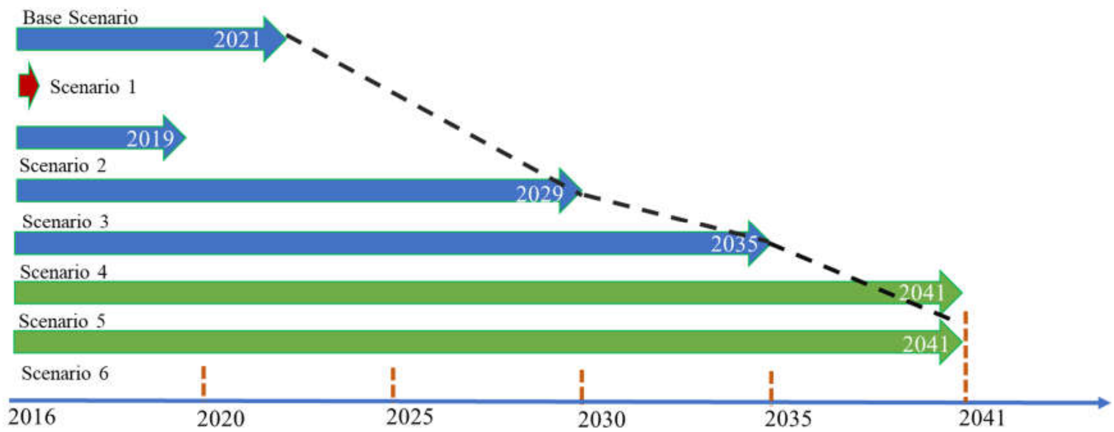

Figure 37: The time range for each of the scenarios under resource limitation.

of the scenarios can be followed as future strategies for water, energy and food. Scenarios with higher self-sufficiency in food production require more land and water. Adopting strategies similar to scenario 1-3 are not sustainable due to the national land and water limit before year 2030. Thus, the country has to switch to low production strategies as it hits land and water resource limitation. The black line in the figure shows when the country might switch to low production scenarios as it will be facing resource constraints under prevailing local characteristics. For all of the mentioned scenarios, only scenario 5 and 6 project to attain SDG 2, 6, 7 and NPI 4, 20 indicators.

6.1 Critical Interconnections

Because of physical limitation, **land resource balance is decreasing because of increasing demand from food and energy subsystems**. Both food and energy production are highly dependent on land use. On the other hand, it cannot be denied other sectors, which are not considered in the defined system has demand for land too. The resource flow for achieving self-sufficiency in food is more influential than land for energy generation. As, Bangladesh is net importer for primary energy with depleting energy resources, land used for electricity generation and distribution has more impact on environment, quantitatively, than land usage. For an 5% increase in self-sufficiency in rice production requires 3% more arable land, 3.8% more water, 3.3% more energy input. In Bangladesh, the demand for cereal based food, especially for rice is high, and attaining 100% self-sufficiency in rice production has been considered as a remarkable achievement by Ministry of Agriculture in past few years. But, the demand for rice will still keep growing and, under prevailing local characteristics, it would demand more land which is already short in supply. On top of it, if agricultural land is used for electricity production, the crop production will decrease. Fossil fuel-based electricity generation takes less land compared to renewable sources. Thus, when environmental concerns are emphasized in future strategic planning, the land demanded might become an issue of contention. Scenario 4 showed that 20% renewable integration was achieved with reduced self-sufficiency in cereals and cash crop. Bangladesh has already been experiencing an annual agricultural land loss at 1% due to urbanization, infrastructure development and climate change (Molla, 2016). The country has also planned to increase its forest covered land to

18% by 2030. The land demand from different sectors and priorities are eminent and the demand for nonagricultural land might be shifted towards arable land. Availability of land is the major bottleneck for food production in the defined system.

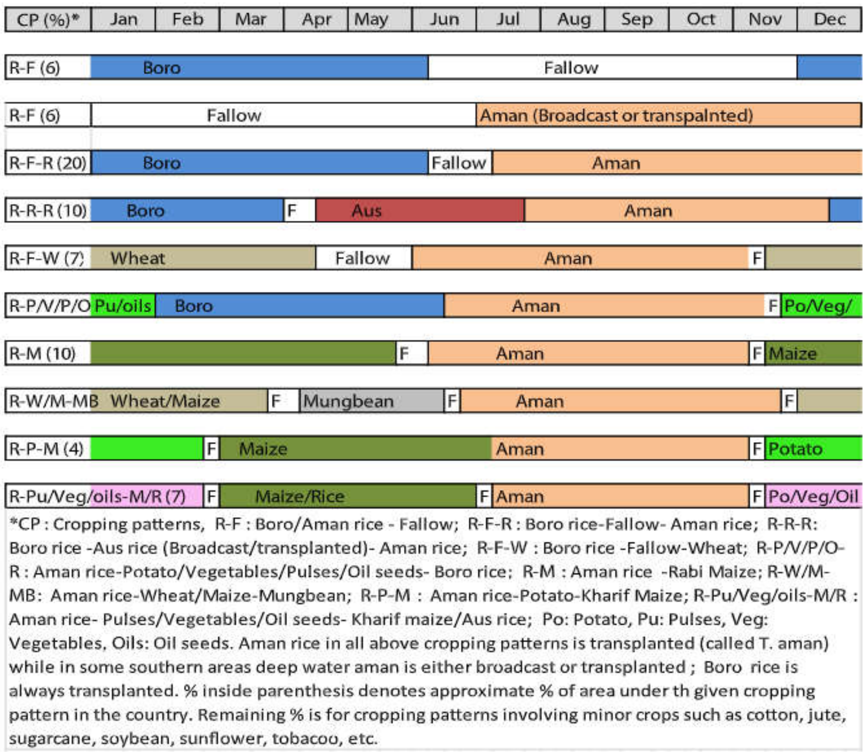

Figure 38: Major cropping patterns of Bangladesh reprinted from Timsina et al. (2016).

Bangladesh has been exhaustively using ground water for agriculture because of lack of infrastructure to access surface water. As the cropping intensity is increasing by year, more lands, previously rainfed, are being brought under irrigation facilities. It is, for the time being, aiding to the volume of production, at the cost of lowering the water level each year. Currently, the annual groundwater withdrawal for agriculture is more than twice than the national ground water reserve. The water withdrawal is becoming much faster than the recharge of the reserve. According to Sweden Textile Water Initiative report 2016, the ground water level throughout the country is on declining trend, especially in highly irrigated areas. The net volume of water withdrawal from ground resources will be around 80-90 BCM, if we want to keep 80% self- sufficiency in food production. Water consumption is also crop specific. Attaining 5% more self-sufficiency in rice will require around 4 BCM water which is equivalent to national water use for domestic purposes. Thus, production driven policies will soon create a significant stress on sources of water. Less than 10% of the total cropped land in Bangladesh is rainfed (AIS 2018). If the major cropping pattern of the country is examined (fig. 38), it can be seen that cropping during the wet season (June to October) is dominated by Aman rice, which has tolerance against heavy rainfall. Other rice varieties have low yield for rainfed cropping than Aman rice. Too much water during rainy season and too little during dry season has been a weather issue in Bangladesh right now. However, due to the prevalence of unrestricted use of ground water for agriculture, more lands are being brought under irrigation for producing crops in dry seasons. That is why building and reviving surface water reserves for irrigation during dry season is one of the objectives of Delta Plan Bangladesh. Currently, there are limited treated waste water facilities for irrigation near city areas of Bangladesh where the water sources are mostly river water, containing industrial, municipal and domestic discharge. Several studies have been made on the impact of treated waste water for peri-urban agriculture for the country (Roy et al. 2015). The crop yield for irrigation using treated water is lower and the chemical input is higher than that of irrigation using ground water thus limiting the possibility of widespread use of treated waste water for agriculture. The pollution level in river water of industrially rich areas in Bangladesh are much higher than the global standard (Arefin and Mallik 2017). Textile factories discharge chemicals including salts, dyes and bleaches, while effluent from tanneries is significantly stronger and contains a range of heavy metals. Most of the domestic, municipal sewerage and industrial effluents are discharged untreated. If the national water policy and water act 2013 is applied efficiently, the opportunity for treated waste water for irrigation will increase.

Carbon footprint is dependent on the choice of energy sources. Emission from fossil fuel has not been seen as a problem for Bangladesh till now, as the country has a per capita emission of 0.4 ton/year, substantially less than the developing neighbors. But the future lies ahead is critical. Bangladesh has already started building 13 coal fired power plants, all over the country, building them at the coastal plains. As the volume of electricity generation is projected to be much higher than present production, 2 times higher in 2030 and 3 times higher in 2041, associated emission is bound to increase. But the volume of emission varies significantly with the choice of energy source. If all these demands are met by a coal dominated energy mix, the volume of emission varies significantly. For example, a 5% increase in the share of coal in the total energy mix for electricity production gives rise to emission by almost 10%, whereas sources such as natural gas and oil contribute much lower to emission. Replacing coal share with renewable energy or carbon-neutral energy sources can decrease the emission by 2% for each percentage of replacement. On the other hand, coal-fired power plants have an average life cycle of 38 years. While the world is switching from coal to cleaner energy, investing in such technology might cause the environmental problem, affecting the soil and water quality in the long run. Nearly 25% of the total energy input in agriculture requires irrigation, which is dominated by diesel-powered pumps (Khan and Hossain, 2007; Khosruzzaman et al., 2010). If this energy comes from solar electricity replacing diesel, it will result in a nearly 25% reduction in emission from agriculture (~4 MT) and savings on fuel cost. The Infrastructure Development Company Limited (IDCOL), supported financially by the World Bank and Asian Development Bank, is working towards financing infrastructure and renewable energy in Bangladesh. 923 of the 1,024 solar irrigation pumps that have been approved by The IDCOL are already operational in the country (Mahbub, 2016). Such irrigation facilities mostly subsidized and withdraw groundwater for irrigation. So, a balanced must be established to regulate the pressure on water sources and limit the emission.

6.2 Potential Interconnections

Bangladesh receives nearly 1122 BCM river flow annually. Such huge reserve remains unutilized in the country for food production. **Shifting the dependency from surface to ground water shifts the stress on ground reserves.** Under local resource flow, 5% shift in share of water usage from ground to surface water means nearly 5 BCM less water being withdrawn from reserve resources. Using treated waste water for agriculture can also replace the pressure on groundwater with added cost of energy. Energy required for waste water treatment varies with technology and infrastructure (.3-2.1 kWh/cubic meter). On the other hand, the purity of treated water depends on the contamination level of the source water (Capodaglio and Olsson, 2020) and the crop yield is also dependent on purity. As discussed earlier, to make treated water more available, national water act 2013 and NWPo can play vital role to maintain contamination in discharge from industrial effluents and municipal sewerage. Currently, only 10% sewerage water is treated before discharge and there is no exact data on how many industries are operating effluent treatment plants efficiently. Crop yield in Bangladesh is connected to water availability and yield for irrigated cereals are much higher than rainfed crops. Other crops such as vegetables, potatoes, spices are season dependent (AIS 2018). However, crop yield potential for rain-fed and irrigated crops are much higher than the actual farm yield in the country. Closing the yield gap and mixing rain-fed cropping with irrigated cropping can increase the self-sufficiency of crop production by reducing the increasing demand of land and water (Timsina et al., 2017).

Ten major crops that were considered in the model, have different yields. Cereals such as maize have high yield than rice. Potatoes and vegetables are also highly productive crops. **Switching from low yield to high yield crop variety might ease the demand of land and water**. In scenario 5, it was seen that with the current resource balance, 100% self-sufficiency in other crops can be achieved (from 90%), without any significant stress on resources if self-sufficiency of cereal is sacrificed by 5%. Such diversification can release the stress on land usage. But it also implies import of cereal and change in diet pattern in future.

Land required by renewable energy technologies might be higher than fossil fuel-based technologies, but with significantly less stress on water and environment. In scenario 4,5 and 6, the net emission due to electricity generation was cut down to half by incorporating 10-20% renewable energy in the energy mix. Poor maintenance of bio mass plants has been a major issue in Bangladesh. In the developed scenarios, the potential for biomass energy was unexplored, but it has lower carbon footprint. As the agriculture sector produces a lot of waste and residues, utilizing this potential will reduce the dependency on energy import too. The assessment tool has the ease to assess the impact of renewable integration for irrigation. Solar integration opens the opportunity for carbon free irrigation, where 100% solar integration can lead to 25% reduction in carbon dioxide emission. Whereas grid electricity emits 600-1000 gCO_2/KWh, solar irrigation can reduce the emission as low as 16 gCO_2/KWh. The impact on land from distributed solar powered irrigation for crop production is not significant. On the other hand, it can be a solution to stabilize crop production in arid areas. Farmers can also save on fuel. But, overall, this can lead to wasteful water use, over-abstraction of groundwater, and low field application efficiency (FAO, 2017). Local government division along with IDCOL and BADC can play a vital role here to promote and regulate solar irrigation in rural areas. Solar power can also be used for treated water facilities, thus reducing the burden on total electricity generation.

6.3 Leveraging the Interconnections

From the assessments for each of the scenarios, it is conspicuous that, the land and water demand for food production is driven by the choice of crops to be produced and the self-sufficiency, predominated by cereal production, whereas, the burden on the water resources can be reduced by reusing waste water up to 5%. The emission is dependent on energy mix and it requires insignificant amount of land and water resources. The main bottleneck for scenario 1-4 including base scenario is the resource constraints of land and

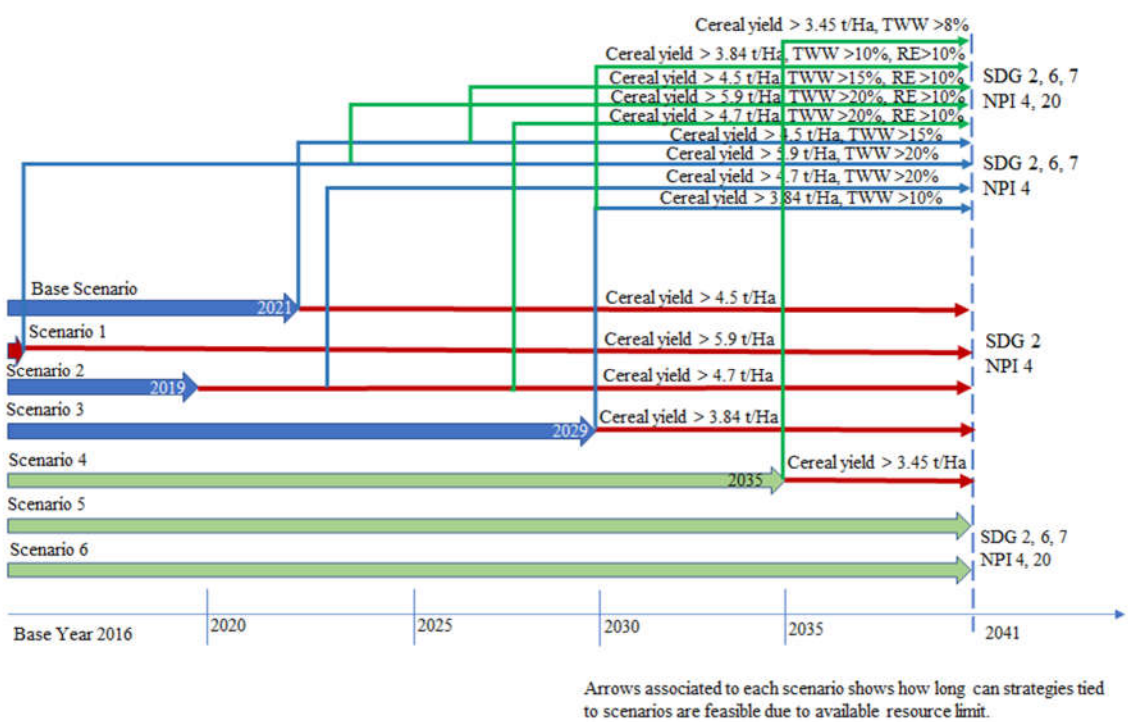

Figure 39: Additional strategies required to attain a set of SDG and national priority indicators for each of the scenarios.

water. Understanding the critical and potential interactions among water, energy and food resources, analysis has been performed to inspect what can be done to ensure that each of the scenarios are sustainable up to year 2041. In fig. 36, it was shown that base scenario is followable up to year 2021, scenario 2 to year 2019, scenario 3 to 2029 and scenario 4 to 2035. If the cereal yield is increased from 3.34 t/Ha to 4.5 t/Ha, the base scenario is achievable within the available arable land. To reduce the pressure on water resources, treated waste water share will have to be increased up to 15% in 2041 to sustain such food production. To attain NPI 20, the renewable energy share has to be increased from 3% to 10%. Thus, to make base scenario attainable up to year 2030 and 2041, cereal yield has to be increased by 4.5 t/Ha, with gradual increase in treated waste water usage by 15% and renewable energy mix up to 10% to achieve national priorities as well as SDG indicators by 2030 and 2041. The fig 37 is used to show how each of the scenarios are attainable if the cereal yield, % increase in treated waste water and % increase in renewable electricity to attain a set of goals and indicators. Scenario 1 is not achievable, even in base year 2016, due to resource constraints. The scenario is only possible to proceed with if the cereal production is raised to 5.9 t/Ha and gradual raise in treated waste water (TWW) share up to 20%. Thus, scenario 2, 3 and 4 will become achievable with maintaining all SDG and NPI indicators by increasing cereal yield and share of TWW.

6.4 Exploring Future Scenarios

If the focus from local characteristics is shifted towards regional or global characteristics of resource flow, it will be seen that, in some cases, subsystems of WEF are consuming more or less resources for same amount of output. **Bangladesh is lagging behind in closing the yield gaps in cereal production than global average**. Moreover, the model assessments and resource balance shows, if surface water resources are managed properly, increased water demand for food can easily be met. In the following, some of the potential future scenarios are discussed.

The relative yield gap for rice and maize production across Bangladesh is around 50% and it is much higher for rainfed cultivation (Timsina et al., 2016). As Bangladesh has a huge challenge in pursuing self-sufficiency in food for its increasing high population, diet changes and limited resource for food production, introducing more high yield variety, changing to high yield cropping pattern might decrease the pressure on land, while accommodating other activities including crop lands for cash crops. The general decrease in arable land has not been considered in the scenarios. For 1% annual decrease in arable land, by 2030, with the crop yield the country has now, it would not be able to produce over 85% of the crop produced in 2016. Bangladesh is also in danger of sea level rise and salinity intrusion in the coastal area. Only one-meter raise in sea level will flood nearly 16% of the net land area of the country. Switching to high yield variety (high yield rice, wheat, maize and jute) and improving yield of different crops through modification in cropping technique (ecologically well-adjusted cropping pattern) might be the only way for achieving food security in future (Timsina et al. 2017, Khan and Hossain, 2007)

As the domestic supply of gas is depleting, Bangladesh is moving towards energy sources that is cheap in global market, at the cost of pollution (PSMP 2016). According to PSMP

2016, Bangladesh has limited potential for hydropower and wind power to generate electricity.

However, numerous researches have pointed out that **Bangladesh produces a significant amount of agricultural and municipal waste** (Halder et al. 2015 and Islam et al. 2014), But, due to bitter past experience in expanding biomass power plants are not well spread in the country. This unused potential should be considered in the national electricity generation planning. It can also reduce the import burden of primary energy for the country. On the other hand, being a country in topical region where sun is bright for longer period of time, incorporating renewable energy for agriculture might reduce emission from mechanical input in agriculture such as solar irrigation.

Bangladesh has vast water resources, spread across the country with temporal and spatial variability. The net amount of river water flow is nearly 10 times than national water reserve in total. **This unused potential should be brought under strategic planning to ensure water availability for seasonal agriculture**. The Delta Plan Bangladesh 2100, is focusing on reestablishing channels between existing surface water bodies and water sources. If the planning meticulously considers water requirement for both ecological protection and agriculture, the dependency on ground water can be reduced significantly.

Bangladesh is vulnerable to climate change and burdened by high population. In the tool, the population growth was playing a significant role as it helped to set the future food demand. If the population growth remains at lower rate, the food demand will be lower, thus pressure on resources will be lower. Scenario 6 has shown for a reduction in population growth by 0.1%, the self-sufficiency in food production can be retained to 80% and higher. However, climate externalities, such as sea rise, drought can also lead to loss of arable land. These uncertainties have not been explored, but the impact, undoubtedly, will be severe.

6.5 Moving Forward: What Can Be Done Next

The assessment does not include any financial instrument. Thus, the financial feasibility of each scenario cannot be shown here, which is also a parameter for STEP 3-filter framework. Moving from production to import decisions and the associated cost and benefits can help the policy makers in taking more clear decisions and strategies.

The assessment tool developed in this study is essentially concentrated in cross sectoral interaction among food production, water and energy. **The scope of the assessment can be expanded by incorporating other sectors in the model**, such as industry (3-4 major groups of industries), fisheries, livestock, forestry, domestic and municipal sectors can be included here as resource consumption systems to assess the holistic demand and impact on water, energy, food, land and environment.

It is highly unlikely that national data represents regional data. With the assessment tool and availability of regional data, the cross sectoral resource demand can be estimated and the resource balance for each region can be checked. It can pave the way of regional resource sharing to reduce local stress on resource. Scenario based framework can also help in development of intraregional and interregional resource planning for long run.

The tool necessarily assumes that resource flow and local characteristics remains same all over the year. But every country experience seasonal change, thus the resource flow and local characteristics might change accordingly. The temporal resolution can be incorporated in the assessment to investigate temporal stress on resources. This can facilitate cropping pattern for different crops to assess the impact. As the tool is used to predict the future interaction, the scope for uncertainty becomes stronger for long term projection than short term projection. There is no certainty that the resource flow and local characteristics will remain same as 2016. **Rather than projecting for long term, we can make short term assessments,** adjust the plans, policies and strategies and move forward. Scenario 3 is a complementary example for such strategies.

6.6 Recommendations

- Land and water being the most connected resource in system defined urges more strategic planning. The trade-offs in setting power plant on arable land to food production must be reflected in long term planning. Thus, Power Division (PD) must consult and inform the Ministry of Agriculture (MoA) and associated ministries in positioning future power plants.

- Surface water resource development should be one of the priority issues in Delta Plan Bangladesh. LGED and BADC should work more connectedly on developing strategic plan for surface water availability where ground water sources are depleting. Treated waste water facilities can be used to reduce water stress where demand is low (domestic, municipal usage and peri-urban agriculture).

- Government can invest in projects which reduces resource loss. A 5% increase in energy usage can reduce emission and demand of energy by 5%. South Asian agriculture is also known for irrigation loss. 5% reduction in total irrigation demand can subsequently replace need of treated waste water facilities for irrigation and reduce pressure on ground water at the same time.

- Two major long-term development plan, Power System Master Plan (PSMP 2016) and Delta Plan Bangladesh (DPB) should be cross screened to identify conflicting and common area of interest. For example, if PSMP becomes more coal-oriented, the adverse effect on water, land and environment should be communicated to DPB via connected ministries as added externality and the plan should adjust accordingly.

- The national priorities should be revisited based on interconnections, not on goals. In scenario 1-3, it is seen that to ensure highest SS% in crop production the groundwater resources were stressed to capacity which remained unacknowledged in national priority.

In the policy analysis, it was seen that the intrinsic interactions among policies inherently sets priorities. Under such conditions, the commonly shared resources might face stress in future. According to the assessment, the trade-off between land for crops and land for energy will be critical in near future. On the other hand, water is abstracted from ground more than its recharge capacity. If the trend goes on, the ground water level will drop more rapidly, especially in northern regions where cropping intensity is higher than national average and rain is irregular. The policies should be revisited to harmonize among the three sectors in order to minimize cross sectoral conflicts and maximize synergies and achieve resource security in integrated manner. When resource interaction is seen through a nexus lens, the trade-offs can be identified more clearly in terms of quantity and priority. For example, the groundwater will be facing more stress if the prevailing water use pattern goes on. Such unsustainable usage practices can be regulated and managed based on the resource availability. Similarly, solar energy for irrigation can limit the emission from using fossil fuel for agriculture. Thus, by examining the key interactions in resources, appropriate and innovative strategies can be coordinated to exploit complementarities and synergies to manage the trade-offs. The analysis done in the previous chapter are done in a monolithic form, it was assumed that the strategies will not change during the course of time for each of the scenarios. The scenarios can be seen as long term or short-term strategies which can be mixed and matched. For example, base scenario can be adopted until 2023, unless any other strategy is taken for which the land and water requirement fell below the resource limit (high yield crop variety, aquaponics, hydroponics etc.), the decision makers can look into scenario 4-6 for future after year 2023. Le Blanc (2015) and IGES report has showed repeatedly that SDG interlinkage have local characteristics and attaining one target have significant impact on connected goals. Thus, the country can revisit its priorities interaction with resources and set informed priorities for future.

7. CONCLUSIONS

Unprecedented risks and challenges involved with resource management can only be understood if it is seen from and interconnected point of view rather than a silo view. Promotion of activities which may seem economically feasible, might bring additional externalities to resource which are limited. Traditionally, resource scarcity involved government through regulation. But, without acknowledging how the core resource, water, energy and food, interacts with each other locally, resources which are abundant and free for today, might fall victim to the need of tomorrow. But, integrated and interconnected policy decisions, acknowledging each other's need and goals, synergies and trade-offs, a better resource management can be promulgated. Bangladesh, which is one sixth in size of Texas, but having a population almost half of the United States of America, has been burdened with the growing need of core resources within its geographic boundary, fulfilling additional goals for economic solvency by the government urges for informed planning, In this study, a WEF system assessment tool was developed for Bangladesh to investigate how the impact on the core resource system for the long term future have been planned. Through the analysis, it was seen that due to unavailability of critical resources, i.e. land and availability of usable water, the future planning that have been are not only unattainable, but also unsustainable, which is against the central notion of sustainable development goal. With the tool, a few alternative scenarios were assessed, which showed us informed management of core resources can help the country in not only achieving sustainable development targets, but also its national priorities. Diversifying production, domestic and virtual sources (Import), the country can sustain such development in long run. But not all scenarios can be implemented without additional strategies. The tool and analysis are done considering many assumptions, which might not be, in real world true. But it ushers a starting point where different ministries, as stakeholders recognize the interaction and tight interconnections in resource management which can promote integrative thinking in the process of strategic planning for future.

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