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Application of energy optimization models to design sustainable energy system: A review

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Abstract– Socio economic development in a society depends on its energy consumption level. Various studies findings on energy indicate that there is a gap between current energy consumption and supply levels. Conventional primary energy reserves will not be able to meet the projected energy demand. So, the present energy system is not sustainable. Alternative resources need to be integrated in the energy supply-mix to meet the expected future energy demand. Fossil-fuel reserve is limited and the use of these fuels has a negative impact on the environment. Holding energy in a secure level and global climate at a safe level requires long term strategy to integrate renewable energy resources/technologies in energy supply-mix to aim of energy sustainability. A sustainable energy system development approach is fundamental and encompasses various aspects such as energy security objectives, environmental impacts, and economic development. The feasibility of a sustainable energy system can be analyzed applying energy models. Energy models are used to help in energy planning, and to assess alternative national/regional energy policies and integration of clean technologies. This paper presents a design concept of a sustainable energy system and reviews its components. This paper reviews different energy models and presents application of some energy optimization models with consideration of innovated clean technologies in the energy supply-mix in order to achieve a sustainable energy system for a society.

Key words–Sustainable energy; energy models, renewable energy technologies; climate change; low-carbon society

I. Introduction

Sustainability of energy is a vital global concern based on universal use of energy, conversion of conventional primary energy to final energy has negative impacts on environment, escalating economic globalization as well as to reach final energy to the global domains. Energy is unswervingly connected to the greater thought of sustainability. The energy sustainability concept provides a framework to evaluate policies considering existing and innovated technologies in energy supply mix to meet the future energy demand [1]. This also guides decision makers to implement projects on energy future.

The measure of national development is identical with the level of energy utilization. So, energy is known as a vital input parameter for development. At present, energy demands are mostly supplied by conventional fuels (oil, gas and coal) and these fuels have limited reserve.

It is important to note that currently world-wide about 1.4 billion of people have no access to electricity and about 2.6 billion of people solely rely on traditional biomass fuel [2], [3]. Fossil-fuel reserve is limited and natural gas, oil and coal may last for about 59, 46 and 118 years respectively, if the present consumption rate is continued [4]. Nuclear fuel reserves also not enough for massive implementation of nuclear power plants for the longer-term period [5]. These data highlight a projected decrease of “energy security”1 and sustainability energy system. Access to modern energy for all is a global agenda and clearly mentioned in the Sustainable Development Goals (SDGs), specifically SDG 7 [3].

Therefore, sustainable development issue in the energy sector is inspiring the requirement to find the alternative paths. Renewable energy resources and their technologies can play a vital role to contribute to the issue of “energy security” and contribute for the development of sustainable energy system [6]. Renewable energy integration would diversify the energy supply mix and provide a secure and continuous availability of energy sources in different forms of energy. The limited availability of fossil-fuel and greenhouse gas (GHG) emissions are the main drivers on finding alternative renewable energy technologies (RETs) to meet the future demand of energy [7].

Renewable energy resources contribute significantly in the method of incorporating national or regional or global energy policies using computer tools or energy-environmental models to develop scenarios towards sustainability. Therefore, energy optimization models play an important role to design policies towards sustainable energy system for a long-term period. The energy models help to implement recent governments Intended Nationally Determined Contributions (INDCs) target, renewable energy production target, etc.

Energy sector development links with other sectors. The link between energy, environment and economic development is often termed as 3Es (Energy-Environment-Economy) concept or tri-lemma concept. The concept is complex. This 3Es concept is an approach that covers mainly three aims namely 1) economic development, 2) secure energy supply, and 3) minimize environmental impacts [8]. Only energy-environmental models are helpful to assess the linkages among the 3Es and their future scenario development [9]. The models consider the environment and the economy in policy planning towards sustainable development.

These models have been used to provide scenarios, forecasts and support decision making in energy planning issues. They are also considered valuable tools for understanding the factors behind the integration of energy technologies and transitions in energy consumption based on different policies or target implications. These additionally serve as support systems in decision making for policy makers and engineers in order to select environmentally clean technologies to understand the economic and environmental impacts of the configurations of energy systems.

The aspects outlined above illustrate those multiple factors linking energy systems towards sustainable development, highlighting the need for measures which are considered clean and RETs under a trans-disciplinary approach. The shift to renewable energy resources and the integration of advanced clean and renewable technologies in the future must be analyzed beyond the assessment of individual alternatives. A sustainable energy system approach is fundamental for effectively integrating the multiple aspects of designing a sustainable society.

II. DESIGN OF SUSTAINABLE SYTEM FOR A SOCITY

Energy systems are mainly a representation of the relationships existing between energy production and the consumption of energy services necessary for human activities with a society. The energy system may correspond to an entire society which can range from a single village or community or a country or group of countries or worldwide. Energy systems have three components, namely 1) energy resources in the form of primary energy, 2) conversion technologies transforming and supplying these resources to users in the form of secondary energy, and 3) energy demand sectors comprising different economic sectors consuming energy [10]. These components can be subdivided further into more detailed sequential steps from the mining of energy to end-use devices by means of what is known as the reference energy system (RES). The RES represents all activities and technologies of an energy system, showing energy demands, technologies and fuel supply-mix to satisfy demand services [11], [12]. The design of a sustainable energy system concerning the achievement of sustainable development according to targets linked to each of the 3Es is given in Figure 1. The figure shows the communication between the design of the sustainable energy system considering the targets and society which require it. Demand side management (DSM) in addition to renewable energy helps to improve energy security. Energy efficiency improvement opportunities in both supply and demand sides need to be assessed. The purpose of energy system design is to find the combination of renewable energy resources that are best suited with government targets under certain constraints and program related to energy efficiency improvement. The targets are used as inputs and generally refer to the achievement of a secure energy supply to the end users. Targets represent the preferences over the energy systems' performance and structure, indicated by energy policy objectives. If the conditions to satisfy the initial applied targets are too strict, then feedback information is needed to process the energy system design. The implications of the sustainable energy vision or energy for all goal in present society must balance the factors related to the 3Es.

The 3Es can be linked to a target for the design of the sustainable energy system. With respect to energy, energy security achievement and energy access targets are the main issues of interest to developed and developing countries, respectively. The energy system and its impact to society are strongly correlated. This correlation is represented in Figure 1 by the input and feedback information flowing between the sustainable energy system and the 3Es of society. The feasibility of sustainable energy system design can be assessed by applying energy optimization models using these targets (renewable production by a certain percentage, GHG mitigation, resource availability, technology integration and efficiency improvement with respect to projected energy demand.

Renewable energy technologies such as solar PV, concentrated solar power (CSP), wind, hydro and geothermal considering their availability for power generation need to incorporate in modelling and also it demands to add technology learning curve effects on cost and efficiency improvement on RETs to find their feasibility. For remote rural areas where grid-connection is not feasible, solar home system, pico-solar, hybrid system, mini-grid would help to minimize use of fossil-fuel. Improved cookstove (ICS) is a very important technology that reduces indoor air pollution, biomass demand compared to the traditional stove.

A. Demand side management (DSM)

In general, in the energy area and power generation in particular, one could securely say that "a Joule saved is worth significantly more than a Joule earned" [13]. It takes significantly more than 1 Joule of energy to generate 1 Joule electricity. Avoidance of consumption by measures such as higher energy conservation efficiency, reduction of waste, and more modest lifestyles, offers the highest impact on the reduction of fuels consumption and importantly, on the associated undesirable emissions and environmental consequences. In the residential and commercial sectors, energy efficiency is generally related to the adoption of more efficient electric appliances, heating and cooling devices. In these sectors efficient design of building is being applied and taking advantages of daylight, incorporating thermal insulation and integrating air conditioning systems with energy use saving structures. Energy demand reduction in the industry sector can be achieved using efficient electrical equipment. To improve DSM, it is fundamental to steer education towards raising awareness in energy end users.

B. Summary

The realization of a sustainable energy system involves shifting from conventional to non-conventional technologies. Such a change can be guaranteed with policies and measures allowing the penetration of current and foreseeable technological innovations in the present energy system. To analyze the possibility of the transition to a sustainable energy system and plan the ways in which sustainable energy can be achieved in the future is a complex task for decision making in energy planning. The design of the proposed system and assessment needs should be based on quantitative methods (models) in order to give more credibility to more feasibility to proposals targeting the sustainable energy system. Quantitative analysis using models offer better understanding of the feasibility of the integration of RETs in the energy sector. The following sections discuss different energy models and the application of some models that deal with integrating RETs into the power sector.

III. ENERGY MODELS AND APPLICATION TOWARDS SUSTAINABLE ENERGY DEVELOPMENT

A. Energy models

Energy planning is an important task for both national governments and international agencies, as it supports decision making with respect to national and international development. The energy planning discipline dates from the 1960s, when the first studies focusing on energy supply were carried out. At that time, planning methodologies focused on different aspects such as cost, environmental damage or energy supply security. After the oil crisis in the early 1970s, energy planning became very important, especially for policy makers. Only after the oil crisis was sufficient attention given to critical assessment of fuel resources, rational use and conservation of energy resources, and long-term energy planning. In addition to this, the Rio Earth Summit in 1992 triggered environmental studies on the issue of GHG emissions. This was especially the case after the report of the Intergovernmental Panel on Climate Change (IPCC) in 1995, which concluded that CO_2 emission has a noticeable impact on the environment. Intensive discussions and debates followed, legislation was formulated and GHG emission reduction

B. Energy supply models

Energy supply models are often concerned with determining the least-cost options of an energy supply system meeting a given demand and subject to a number of constraints. These models generally use an optimization or a simulation method, where the optimization is usually based on linear and non-linear programming. Some of the energy supply models are extended to include parts of the energy demand analysis, and others provide additional features to calculate the impacts on the planned energy system including emissions, economic and social aspects. Representative energy supply models are: MARKAL/TIMES, MESSAGE, POLES and WASP.

MARKAL (MARKET Allocation) is an energy planning targets set (e.g. the Kyoto Protocol). Aggregated energy-related activities contribute 80% to the total greenhouse effect worldwide [14]. This has created a need for new energy planning models that consider environmental problems. Therefore, besides separate models for environmental studies pertaining to assessment, projection and mitigation, energy planning models were expanded to cover the environmental aspects of power generation.

Energy planning models differ from each other in the model purpose, model structure (e.g., internal and external assumptions), analytical approach (e.g., top-down or bottom-up), study methodology, mathematical approach, geographic coverage, sectoral coverage, time horizon, and data requirement. Table 1 presents energy-environment-economy models that are used for energy and environmental policy analysis. The most important models and practices that have evolved in the field of energy-environmental planning are macroeconomic models, energy-demand and energy-supply models, modular package models and integrated models.

The following section discusses on energy supply models these are more useful for policy design towards sustainable energy system and meeting to goal of energy access to all and improve energy security.

model that was developed by a consortium of members of the International Energy Agency (IEA) in 1976 just after the oil crisis. This model is based on the General Algebraic Modeling System (GAMS) – a computer language specifically designed to facilitate the development of algebraic models. TIMES (The Integrated MARKAL-EFOM (Energy Flow Optimization Model) is the successor of MARKAL model. The both model share same paradigm of modelling. The TIMES and MARKAL models are technology explicit, dynamic partial equilibrium models of energy markets/systems. The objective function of both model is to minimize the total system costs and optimal use of resources. These tools are very useful to design long-tern alternative policy scenarios towards sustainability of energy and climate issues. The MARKAL/TIMES has been adopted in energy and environmental studies in over 70 countries and one of the most widely used energy models in the world [16].

The MESSAGE (Model for Energy Supply Systems Analysis and their General Environmental Impact) was developed by The International Institute for Applied Systems Analysis (IIASA). This model is a dynamic linear-programming model, scheming cost-minimization energy supply structures under different constraints. The model uses two major types of variables: an activity variable (describing the fuel consumption of technology) and a capacity variable (annual new installations of technologies). The constraints applied in all modeling exercises are acquiring sufficient supplies of the exogenous demand, balancing quantities for all energy carriers and periods, constraining resource availability, and ensuring the installation of sufficient capacity of the technology applied. The objective function generally applied in MESSAGE is to minimize the sum of the discounted costs [17].

The POLES (Prospective Outlook on Long-term Energy Systems) tool is a simulation modeling framework that provides long-term energy demand-supply scenarios on the basis of hierarchical systems of interconnected sub-models at different scale of use such as national, regional and global scales. The impact of the emissions reduction strategies on the international energy markets can be assessed. A detailed description of the oil, gas and coal market at a global scale allows a significant increase in the size and complexity of the model development [18].

The WASP (Wien Automatic System Planning Package) tool permits the modeler to estimate an optimal expansion plan for a power generation system over a long-term period within the constraints applied by the model use. The model is maintained by the International Atomic Energy Agency (IAEA), which has developed four versions of the program. In WASP model, the

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optimum expansion plan is defined in terms of minimum discounted costs [16].

IV. Application of Energy Models to Implicate Renewable Energy Technologies

We have many challenges to meet to design energy system. As discussed, focus should be given for transformation to sustainability. Climate change, Paris agreement, energy security, reliable modern energy access to all, energy poverty and impact of climate change need to consider to design policies towards sustainability. The energy, environmental and economy models are a useful tool to point out in which direction we should go and which viewpoint we are speaking from, and this enables clearer future decision making.

Each country has its indigenous conventional and renewable energy resources, national development plan and also energy security concerns. So, the best policy or strategy for each nation will be different. As mentioned above, this review looks forward to sustainable development through developing a sustainable energy system. We discussed the appropriate energy models that provide key information for policy makers in the electric energy supply-side faced with navigating a sustainable development path in a least-cost way.

The possible strategies must be evaluated in light of RETs costs, available resources and implications for national energy security. The challenge is in finding an optimal way where energy security, environmental constraints and economy were taken into consideration. Integrated analysis that includes 3Es models will serve an important role in discovering the most suitable scenarios for any national or regional or global energy system towards achieving sustainable development goals.

A. Application of MESSAGE-MACRO model

Ger Klaassen and K. Riahi, 2007 analyzed the global impacts of a policy that internalizes the external costs from electricity generation [19]. The authors used a combined energy system model of MESSAGE and MICRO model. The starting point of modeling was to estimate the monetary damage costs for SO2, NOx and the PM per unit (kWh) of electricity generated. The study tried to answer that what would happen if all external cost of fossil-fuel based power generation are internalized in policy analysis and due to implication of externalities what will be the choice of technologies and energy supply-mix.

The macro-economic model called MACRO was applied to estimate the economic impact of externalities. Linking MACRO and MESSAGE models permit to estimate internally consistent projections of energy and energy system costs. The study developed two scenarios 1) baseline scenario: the scenario based on IPCC's special report on emission scenarios [20] and 2) externality scenario based on the external impacts (monetary) per unit of electricity

The study found that the changes in primary fuels use in the electricity sector when the external costs are internalized in modeling between 2010 and 2050. The study found the winners are renewable energy resources and RETs help to develop low-carbon society and minimize external effects from power generation. The study also found that the contribution of these renewable energy resources increases by more than 40% in externality scenario compared to the reference scenario.

Another study was done by [21] using MESSAGE-MACRO to see the influence of energy supply costs as calculated by the MESSAGE model in the optimal mix of production factors included by the MACRO model. The study found that overall primary energy consumption is reduced by 10% by 2100 in mitigation scenario compared to the reference case with a decrease in coal consumption by 70%. Renewable and nuclear reactors account for more than two-third of primary energy supply. Another similar study on long-term energy supply strategy for Syria using the MESSAGE model with implications of national resources availability constraints was carried out by [22].

B. Application of POLES model

Peter Russ and Patrick Criqui, 2007 applied a method to drive regional emission targets using the POLES energy model for power sector [23]. The study corresponded to an emission trajectory to stabilize CO_2 concentration at 550 ppmv by 2030. A reference scenario and an alternative soft landing scenario were assessed. The alternative scenario applied a logical approach taking into account the constraints imposed by energy, economy and climate dynamics in each region of the world. The method was based on the Kyoto approach that differentiates targets according to group of countries. The POLES reference scenario represents a description of the future world energy system under a continuation of the on-going trends. In this scenario, no policies are included to reduce CO_2 emissions. The following integrations were considered for the soft landing scenario in modeling:

1) To achieve stabilization of CO_2 emission at 10 Gt by 2030
2) To achieve Kyoto targets by Annex I countries (except USA)
3) To reduce emission growth rate linearly for developing countries.

The impact of the soft landing scenario for power generation technologies was compared with the reference scenario technologies. The model suggests to invest on nuclear, natural gas based combined cycle and RETs. The study found a market shift in the power generation technologies. Advanced gas-based combined cycle power plant, nuclear power plant and renewable-based power plants add roughly 1500 TWh by 2030 and the conventional coal-based power plants loose around 6000 TWh generation by 2030.

C. Application of WASP model

The impacts on costs of integration of RETs for power generation was assesses by Poullikkas et al., 2011 using WASP model [24]. The authors did a case study for a small isolated power system for the island of Cyprus to achieve optimum cost of electricity production from conventional and RETs. The method enables the estimation of the optimum feed-in-tariff to be offered to implications of RETs, the overall cost increase in the electricity sector and also the capacity to be implemented based on demand. The study considered the technical and economic parameters for each of the existing and committed power plants of the Cyprus power system during 2010-2020. The considered four RETs namely 1) solar PV, 2) Wind 3) Biomass and 4) concentrated solar power (CSP) technology with 6 hours' thermal storage. The study simulated five scenarios: 1) BAU scenario that expanses natural gas combined cycle technologies of 220 MW without RETs, and 2) 10 to 25% renewable target scenarios (10%, 15%, 20% and 25%, respectively) of total expected demand in 2020. The expansion of RETs to satisfy the minimum trajectories as set in European Commission and the remaining capacity to be satisfied by natural gas combined cycle.

The study found that the electricity generation cost of all selected RETs are decreasing trend. The study clearly also presented the rate of decrease of solar PV is higher than wind. The model finds that the least-cost technology is biomass and most expensive one is CSP. The study concluded that solar PV and wind play would plan an important role to meet electricity demand.

D. Application of MARKAL/TIMES model

Mallah and Bansal, 2010 used MARKAL model to integrate renewable energy for sustainable Indian power system development [25]. The authors claimed that the path towards sustainability is exploitation of energy conservation and aggressive use of renewable energy resources. The study developed three scenarios to implement renewable energy for the Indian power sector: 1) a reference scenario without any policy option, 2) a renewable energy technology scenario that considers the government policies towards renewable energy implementation, and 3) an aggressive renewable technology scenario which considers the full exploitation of renewable energy potential existing in the country between 2005 and 2045.

The study found that coal and hydro power share remain stagnant between 2015 and 2035 in the alternative scenarios. The nuclear, wind and other renewables rise steadily during that period. After 2040, coal generation decreases sharply, whereas nuclear, hydro and renewables rise steeply to meet the desired demand. The study concludes that aggressive renewable technology implementations in the power sector will give Indian energy independence in the future and equally reduce the CO_2 emissions.

Another study was carried out for the Bangladesh power sector to promote RETs for power generation in [26]. The study developed a reference and four alternative policy scenarios in the MARKAL modeling framework to optimize use energy resources for power generation. Targeted CO_2 emission mitigation and carbon taxes of fossil-fuel use were imposed to find technology selection in a least-cost way to meet the future electricity demand considering limited reserve of natural gas in Bangladesh and huge potential of RETs.

The study found that constraints on CO_2 emissions reduction and carbon taxes on fossil-fuel have positive impacts on energy security of Bangladesh. The energy security issue was analyzed in terms of changes in net energy import dependency and diversification of energy resources resulting from the alternative policy options toward sustainable energy system design. The study estimated that about 4.85% of total system cost during the study period (2005-2035) compared to the reference scenario would increase to meet the 10% CO_2 emissions reduction targets.

Import dependency reduces up to 63% compared to the reference scenario during the study period and this would help to improve energy secuirty and develop low-carbon society due to introduction of solar and wind in the power generation supply-mix. The study concluded that the renewable based power generation cost, specifically solar PV, is relatively cheap in Bangladesh and it could be attractive for developed countries to invest in solar PV based power generation in

V. CONCLUSIONS

This study reviews sustainable energy system development approaches and role of energy models to integrate in the energy supply-mix to mitigate GHG emissions and improve energy security in a least-cost way. This reviews find that designing a sustainable energy system is a complex task and it involves multiple challenges. The growing concerns about energy security issues and the negative impacts of climate change on the global environment make energy an important feature of sustainable development. As fossil-fuel reserve is limited and GHG emissions mainly come from these fuels, driving societies or nations towards a sustainable path, is necessary to integrate renewable energy resources to generate final energy. A sustainable energy system needs to shift to renewable energy resources, guarantee the implementation of advanced RETs with higher efficiency and conservation of energy uses by the end usersW.

An energy model is a tool for decision making for a variety of purposes such as energy security improvement, climate policy, and advanced technology assessment. The model can be applied to find the feasibility of sustainable energy system for a society or country or worldwide. It is possible through modeling to Bangladesh to reduce their committed CO_2 emission defined in the Kyoto Protocal through the Cleand Development Mechanism (CDM) projects.

Many studies have been done for the development of sustainable energy sector worldwide based on the MARKAL/TIMES model. Application of these models will help to advices for alternative policy option for tranformation to sustainabilityintegrate all concerning aspects of sustainable energy system and the 3Es. Model provides future scenarios to support policy making in energy issues. The presented application of models in this paper provide insights into the feasibility of implications of RETs in the energy sector. There are many policy options to integrate RETs to designing sustainable energy system.

The model developed alternative scenarios would help in planning to invest and also to minimize the investment risks. Model based different possible options are not only predictions but also credible, challenging and relevant alternative possibilities that help explore the what, if and how.

Therefore, models are useful for assessing the feasibility of energy systems in different policy scenarios but should not be assumed as certain forecasts. Models provide the insights into the implications of different technology options that can be pursued based on targeted policy options towards sustainable development.

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