Modeling and Optimization of Sustainable Energy Generation

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Summary
A dynamic model has been presented in this paper to determine the sustainable energy generation from different sources using optimum control strategy. Applicability of the model has been exhibited by considering a couple of case studies; first an incremental power system in South Asia and second a steady power system in North America. In either case energy planners need to optimize the energy generation from competing sources for both economic growth and sustainability. The case studies provide an overview of the impact of selecting different energy systems and approaches on sustainable energy management system. Short- or long-term planning based on the optimum control theory determine the most economic energy generation by minimizing the cost. The model also adopt algorithm to quantify the system parameters for optimum operation. However, the control strategy needs to be adjusted based on the initial conditions such as current generation, energy system description and forecast demand and generation. These parameters vary for different power systems due to the difference of available energy sources, energy infrastructure, as well as, socio-political differences.
Key words:
Modeling, optimization, optimal control, sustainable energy.

1. Introduction

Due to the huge population of the developing countries with growing economies led the need for modern energy services considering the participation of global transition for clean, sustainable, and low-carbon energy generation. In developing countries, there is an increase in the demand for energy which is due to the recent economic growth in these countries. To meet these types of challenges, reliable, sustainable, and acceptable energy generations are the key steps to alleviating extreme poverty and meeting other societal development goals while considering the emission and cost from the selected fuel sources that are contributed to meet the growing energy demand, causing environmental problems, such as climate change and harmful air quality, that put the health and prosperity of people around the world. For large economy in the developed countries, the growth is consistent. A case studies has been presented in for the optimum uses of fuels for energy generation while considering emission and cost for sustainable energy system [1], [2]. The importance of coal, to meet the ever-increasing demand of load while considering the significant externalizes with human health and potential climate change impacts is discussed in [1]. A dynamic model has been presented in [3] which discusses a temporal evolution of two energy sources; namely, renewable sources and conventional/fossil sources in terms of levels of power generation. For developing an optimum decision policy for the gradual adaptation of renewable and clean sources instead of conventional energy sources is presented in [4] using optimal control theory. To make the energy systems sustainable, strategic different measures need to be taken depending on the country's infrastructure, available energy resources, environmental responsibility etc. [1], [2], [5]. In this paper, we are reporting a numerical study to find the optimum policies for electricity generation from cleaner and sustainable energy sources. Optimum control model was used to determine the state of generation while keep the generation cost at minimum [3], [4]. We chose Lagrange method for the mathematical model.

The increase of demand in energy is due to the exponential increase in population in the developing countries. Furthermore, Green House Gas (GHG) emission and global warming phenomenon are critical due to the use of conventional method of power generation by most of the countries as using existing method for energy generation seem cheap. Achieving a sustainable energy system requires strategically different measures to integrate clean and sustainable sources of energy, such as nuclear power, hydroelectric power, and international imports, into the power generation system for enabling cost-effective and environmental-friendly power generation. The main objective of this study is to find an optimal policy for electricity generation from clean, economical and sustainable energy sources.

This paper is an extension of our previous paper in which we developed a dynamic model to find the optimum control strategy by integrating various energy sources in a growing power system in Bangladesh [2]. While this paper

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focuses on the energy generation for four types of DGs and analyzes the impacts of reducing dirty sources while considering the importance of clean sources for sustainable energy management purposes.

The paper is organized as follows. Section 2 presents the mathematical modeling of the sustainable energy generation system considered in this study. Section 3 illustrates the optimization technique used to optimize the energy generation from different sources. Section 4 validates the proposed optimization technique and presents numerical results based on real-time data collected from US Energy Information System followed by conclusion and future work given in section 5.

2. Modelling of Sustainable Energy Generation

This section illustrates the mathematical modeling of sustainable energy generation system considered in this paper. The equations for the mathematical model are as follows:

$$\dot{x}_i(t) = \frac{dx_i(t)}{dt} = \alpha_i x_i(t) - \sum_{j=1, j\neq 1}^{n} \beta_{ij} x_i(t) x_j(t) \qquad (1)$$

where n is the number of energy sources, α_i and β_{ij} are the model parameters, $x_i(t)$ is the state of energy source i at time $t \geq 0$. Here, $x_1(t)$, $x_2(t)$, $x_3(t)$, and $x_4(t)$ are the states of the energy generation from sustainable base unit, gas, coal, and liquid fuel source. Note that α_i is the percentage growth rate of the i^{th} energy source. Let $I \equiv [0,t_f]$, for $t_f > 0$, denote the plan period of the sustainable energy generation system. The model parameters β_{ij} signifies the growth rates of different power sources. On the other hand, depending on the value of intercept coefficients, the penetration of the different fuel sources varies.

Let $\alpha_i \equiv u_i(t)$ denote a time dependent control variable and for $t \in I$. The upper bound (lower bound) of u_i at time t is assumed to be one (minus one), meaning that the percentage growth rate (retirement rate) is not allowed to exceed hundred percent.

3. Optimization of Energy Generation System

In this study, we expect gradual replacement of dirty and expensive power sources with clean and sustainable sources. The planners must consider the desirable goals as well as the costs of implementation. Thus, the cost function can be considered as:

$$J = \frac{1}{2}\int_0^{t_f}\left[\sum_{i=1}^{n} w_i \left(x_i(t) - x_i^d(t)\right)^2 + \sum_{i=1}^{n} q_i u_i^2\right] dt + \frac{1}{2}\left[\sum_{i=1}^{n} v_i \left(x_i(t_f) - \bar{x}_i^d\right)^2\right] \qquad (2)$$

The cost function (2) is divided into three terms. The first term, the running cost, represents the difference between actual generation and the demand of load at any time during the plan period. The second term of the cost function is the cost related to control efforts. This control cost is determined by the level of investment towards integration of gas, coal, picking source, and energy imports. The third term is the terminal cost that represents the mismatch between the actual generation level reached at the end of the plan period and the target of that period. The state $x_i^d(t)$, for $1 \leq i \leq n$, appearing in the running cost are the desired levels of generation from sustainable base unit, gas, coal, and liquid fuel sources, respectively. The demand and the socio-economic factors need to be considered to this cost function [3], [4].

In this present study, we consider the final desired energy production levels from competing sources according to different planning scenarios some of which are mentioned in the later numerical results sections. The parameters w_i, q_i, and v_i are the weights assigned to specific terms of the cost function.

4. Validation and Testing

This section is aimed to validate the proposed model using numerical simulations and test the optimization performance using real-time data collected from US Energy Information System. The main steps that are followed for developing the proposed optimized sustainable energy generation algorithm are given below.

Step # 1: Sample the time instant $t \in [0,t_f]$ as $t_k = kT$, with T being discrete period (in years) and $k = 0,1,...$.
Step # 2: Compute the cost using (2).
Step # 3: Compute u_i, for $i = 1,...,$.
Step # 4: Compute x_i, for $i = 1,...,$
Step # 5: Follow the above three steps until time instant $t_k = t_f$.

We took a rapidly evolving power system in South East Asia: Bangladesh Power System (BPS) as one example for case study. Based on the forecast load and planned generation expansion of BPS, we calculated the EEG from 2016 to 2025 [6], [7] the normalized value of which has been shown in Fig. 1. The EEG has measured all types of available fuel sources in the Bangladesh Power System. We considered [2] the available imports, hydro-electric, and nuclear as the sustainable base source. Along with the sustainable base source, gas, coal, and liquid fuel have been considered the remaining fuel categories. For the optimization process, four variables were grouped and

normalized with respect to the total generation[1](see Fig. 1). We took a rapidly evolving power system in South East Asia (Bangladesh Power System) as an example case study. The main fuel sources of electric power in the Bangladesh Power System are hydroelectric, natural gas, and coal. Even though there are discernible contributions from other sources, such as, high-speed diesel (HSD), superior kerosene oil (SKO), and furnace oil (FO) [6], [7].
Bangladesh is a tropical country where two major rivers from the Himalayas (Ganges-Brahmaputra) makes the land fertile and very sensitive to the environmental pollution. Its geographic location and climate require energy planners to follow a policy of gradually replacing polluting and expensive energy sources with clean and available generators [2], [7]. We implement the optimum control algorithm described earlier in our program implemented in MATLAB to evaluate the state of the energy generation at a minimum cost. The model provides the final cost of implementation as 0:2288: It is clear from Fig. 1 that power generations from sustainable base sources for BPS rise within the plan period. Fig. 2 shows the normalized power generated from competitive sources for the plan period of 10 years when the control policy was applied.

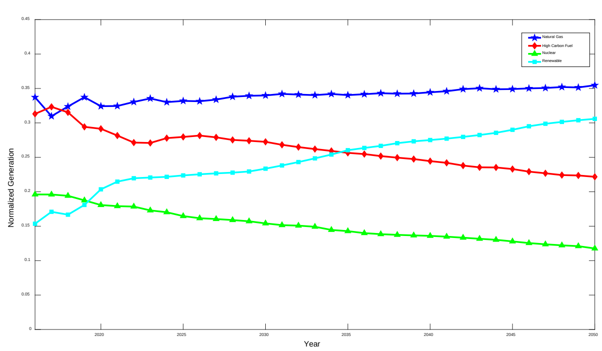

Fig. 1 Expected energy generation of the plan period of 10 years.

Fig. 2 shows the comparative results between the desired value and achieved value after implementing the optimum control theory. The trend of the dirty and expensive source-based generation has decreased over the plan period. On exception is that the generation from coal initially increased and later decreased. It is mainly due to implementation for control strategy for minimizing the cost. The reason for increasing power generation from traditional sources is to meet the rising demand by compensating insufficient generation from dirty sources. The plot indicates the sustainable base source, which started from the normalized value of 0.08, reaching 0.23 at

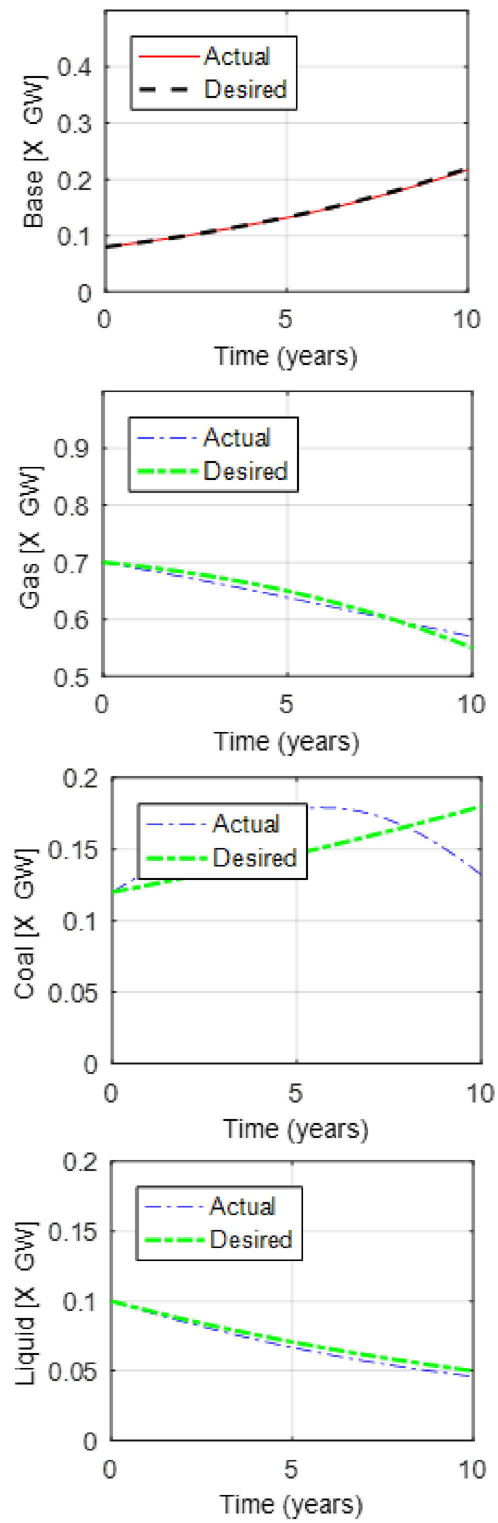

Fig. 2 Comparison between desired and actual energy generation for the expected case.

different fuel source. Fig. 4 shows forecast energy generation for US system. Where use natural gas, nuclear

[1] Bangladesh Power Development Board (BPDB), Annual report, 2014-15 (Accessed April2016)

the end of 10-year plan period. In contrast, the remaining fuel sources such as gas, coal, and liquid fuel have opposite trends over the entire period. A noticeable difference is observed between these two values for generation from coal. This tradeoff is imminent for minimizing the cost. Fig. 3 shows the cost verses number of iterations. The results revealed that the cost value lowered when more iterations have been done.

The trend of energy use for larger power system such as system in USA or similar industrially developed country experience steady growth of energy demand. However; to optimize it, we need to consider not only the price but also the environmental impact of energy generation from different fuel source. Fig. 4 shows forecast energy generation for US system. Where use natural gas, nuclear and renewable sources as base or relatively cleaner sources. On the contrary we consider coal and liquid fuel as polluting sources.

For this larger system focus for optimization is to reduce coal or other polluting sources and increasing renewable and natural gas [1]. The detail optimization technique considering the cost and environmental impact will be reported in the future.

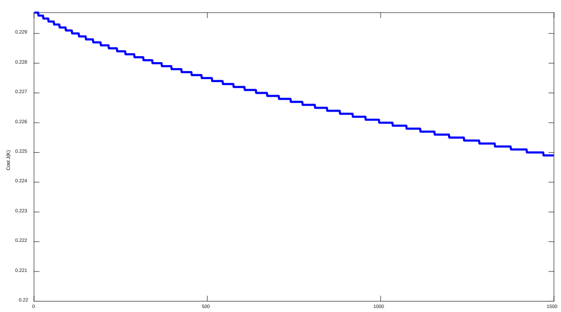

Fig. 3 Cost versus number of iterations

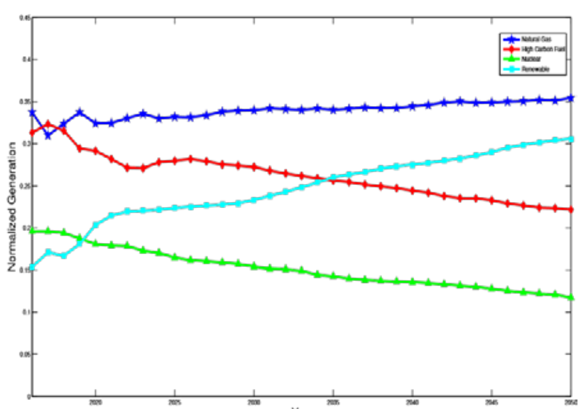

Fig. 4 Energy generation for US system.

[1]U.S. Energy Information Administration, Annual Energy Outlook 2018

5. Conclusion

This paper focuses on the energy generation for four types of DGs and analyzes the impacts of reducing dirty sources while considering the importance of clean sources for sustainable energy management purposes. The case studies show that the actual and desired energy generation from base, gas, and liquid show almost the same trend over the period except coal that shows unexpected difference between actual and desired generation. In addition, the cost function shows the minimum position after several iterations revealing downward trend. Therefore, selecting appropriate fuels for the energy generation will have significant impact on energy management scenarios using optimum control theory.

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