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# Long-term optimal energy mix planning towards high energy security and low GHG emission

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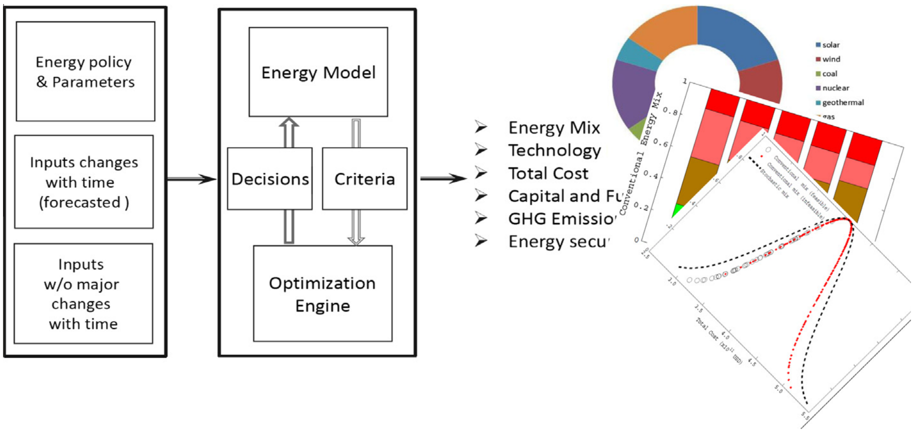
## HIGHLIGHTS

- We develop long-term energy planning considering the future uncertain inputs.
- We analyze the effect of uncertain inputs on the energy cost and energy security.
- Conventional energy mix prone to cause high energy cost and energy security issues.
- Stochastic and optimal energy mix show benefits over conventional energy planning.
- Nuclear option consideration reduces the energy cost and carbon emissions.

## GRAPHICAL ABSTRACT



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## ABSTRACT

Conventional energy planning focused on energy cost, GHG emission and renewable contribution based on future energy demand, fuel price, etc. Uncertainty in the projected variables such as energy demand, volatile fuel price and evolution of renewable technologies will influence the cost of energy when projected over a period of 15–30 years. Inaccurate projected variables could affect energy security and lead to the risk of high energy cost, high emission and low energy security. The energy security is an ability of generation capacity to meet the future energy demand. In order to minimize the risks, a generic methodology is presented to determine an optimal energy mix for a period of around 15 years. The proposed optimal energy mix is a right combination of energy sources that minimize the risk caused due to future uncertainties related to the energy sources. The proposed methodology uses stochastic optimization to address future uncertainties over a planning horizon and minimize the variations in the desired performance criteria such as energy security and costs. The developed methodology is validated using a case study for a South East Asian region with diverse fuel sources consists of wind, solar, geothermal, coal, biomass and natural gas, etc. The derived optimal energy mix decision outperformed the conventional energy planning by remaining stable and feasible against 79% of future energy demand scenarios at the expense of 0–10% increase in the energy cost. Including the nuclear option in the energy mix resulted 26.7% reduction in the total energy cost, 53.2% reduction in the GHG emission and guarantees feasibility against 79% of future energy demand scenarios over a 15 year planning horizon.

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## 1. Introduction

High demand growth, limited fossil fuel reserves and climate change are driving us to target cost effective, energy security and low emission energy planning for the future. Global $CO_2$ emission reached 31.7 $GtCO_2$ in 2012, of which 42% attributed to electricity and heat generation [1]. Therefore, there is an increasing effort to source energy from carbon neutral alternative energy sources, lower carbon intensity fossil fuels and sequestrate carbon [2]. Fossil fuels such as coal, petroleum and natural gas produce large quantities of relatively cheap energy however with GHG emissions. In contrast, renewable sources produce clean energy from solar, hydro, wind, geothermal and biomass sources. Although renewable sources include environmental benefits, the energy cost and feasibility of renewable sources are highly dependent on the renewable potential of the region and weather conditions. For example, solar power is intermittent, biomass could be inadequate in some regions such as a desert, and the wind can be hard to predict. Thus, in many countries, the fossil fuel contribution is important in the energy mix to overcome the shortcomings of renewable sources. How should the energy policy that determines the energy mix be developed for a region? The energy mix recommended by long-term energy planning is based on the future projections of energy demand, fuel cost and technology cost, etc. However, some of the future projections are prone to deviate due to factors such as international action, macroeconomics, population and urbanization. The uncertain inputs could affect the performance and produce risk of high energy cost and insufficient generation capacity. This study proposes a long term energy planning methodology to derive the stochastic and optimal energy mix, and investigates the risks associated with future uncertainties on the performance parameters such as energy cost, energy security and GHG emission.

### 1.1. Evolution of energy models

Energy planning is designing the best energy mix by optimizing performance parameters such as energy costs, emissions and fuel diversity using appropriate energy models. Work so far in this area addresses key issues such as economic feasibility, renewable penetration, reliability, and environmental issues [3,4]. Most of the studies recommend the fuel sources using energy models based on energy cost [5]. An optimal renewable energy model (OREM) designed a renewable system based on the renewable potential, cost, efficiency, social acceptance, and reliability [6]. An integrated energy optimization approach developed in [7] includes the environmental factors (green house effect, acidification, winter and summer smog, etc.) not considered in the OREM. The energy planning decision is optimized with respect to economic, environmental, and combination of costs by converting the environmental impact into equivalent cost. The planning horizon has extended more than a decade using multi-period energy model by considering changes in fuel costs, construction time of generation technologies, and $CO_2$ emission limits. Constructing new and retrofitting the existing plants are additional decisions derived from multi-period energy models [8]. Ding and Somani [9] developed a parallel long-term energy planning model: one model on hour period and the other model on yearly period. They explore the relation between the energy policy and required capacity expansion of renewable and fossil resources. Koltsaklis et al. [10] recently developed a nearly complete mixed integer linear programming (MILP) model to derive optimal energy planning for Greece during 2012–2030. The developed MILP model formulates a country or region into multiple zone networks interacting each other. The primary objective is optimizing the total discounted cost by deciding the right power generation technologies, fuel types and plant locations. The future projections of electricity demand, fuel prices, technology cost, $CO_2$ penalty and even future electricity import prices are considered as known (certain) values. For example, the annual electricity demand assumed to decline 2.5% in 2012–2014 due to the economic crisis, and expected to grow 6% during 2014–2021, and transform to establish growth of 1.1% during 2021–2030. Meza et al. [11] developed multi-objective generation expansion planning (GEP) problem to optimize the investment decision WHAT, WHEN and WHERE to build new generation units during the 10 year planning horizon. The technology costs of new equipment, investment constraints, generating capacity, production costs of generating units and electricity loads are considered as known values. Most of the energy planning decisions were based on future projections available at the time of planning, if any deviation from the projected values could lead to sub-optimal or infeasible solution. A sub-optimal or infeasible solution result in high-energy cost because of under-utilization of resources or lack of production requires a high energy import.

Although, industry practitioners and policy makers make projections of future energy demand, fuel price and other critical inputs to a reasonable extent, the effect of uncertainty is not considered in energy planning models [8–11]. Either the uncertainty in the future projection is assumed to be insignificant or planning has been carried out in a conservative manner. Nevertheless, the projected variables are prone to deviate due to factors, including international markets and internal economics, etc. Long-term energy planning decision based on one scenario of future projection could result with high risk of energy cost and inefficient resource utilization. This paper investigates the relation between uncertain inputs and the risk associated with the conventional energy planning, and proposes the stochastic and optimal energy planning methodology to reduce the risk without violating the policy regulations.

### 1.2. Stochastic energy planning

Stochastic methods are well known in the field of operations research which address the problem of uncertain inputs changing over the time horizon [12,13]. Bakirtzis et al. [14] summarized the modeling approaches in energy planning which accounts uncertainty in the projected inputs. Barforoushi et al. [15] generated future energy demand and fuel prices using Markov chains to study the effect of regulatory intervention on the dynamic investment of power generation in electricity markets. Tekiner et al. [16] investigated the 15 year investment and capacity expansion problem using 1500 energy demand scenarios. Monte-Carlo method generated the scenarios randomly from the predefined demand interval and probability of the load model [17]. Monte-Carlo, probabilistic and scenario development methods [18,19] are the dominant methods practiced to represent an uncertain input parameter evolving over the time. Monte Carlo is a random generation of information from the defined continuous distribution, whereas the probabilistic and scenario-based methods approximate continuous distribution into discrete scenarios [20–22]. A conducive way to describe an uncertain input is defining a system of diverse scenarios as shown in Fig. 1. A scenario $s$ is a path from the root node to a leaf node realized with a probability of $p(s)$ in a scenario tree. The primal condition is at any particular time period the sum of corresponding probabilities is equal to unity ($\sum_s p_{t,s} = 1$). The number of finite scenarios (NS) is the combinations of possible $N$-stages values evolves during the time period '$T$' [13] (Eq. (1)),

$$s \in s_1, s_2, \ldots, s_{NS}; \quad \text{NS} = N^T \tag{1}$$

In stochastic energy planning, at the end of each period $t_i$ the energy mix is decided for the period $t_{i+1}$. For example, at the root node (at time instant 0 and at the beginning of period 1) decisions