Abstract

We have dealt with the problem arising from the incongruity between the evolution of the electricity system for meeting the objectives of economic growth, and the human/societal requirements of inclusive and affordable development, and environmental compliance, within the purview of sustainability. We conceive and define the concept of sustainability in the context of national electricity system and adopt an indicator-based hierarchical framework to assess, measure and track its sustainability. The approach necessitates prioritization, quantification and aggregation of multi-dimensional indicators of sustainability. We evaluate the Indian electricity system using this framework by benchmarking the actual dimensional indicator values against upper and lower threshold levels to compute a national electricity system sustainability index (NESSI) for India. The estimated NESSI value for India in 2013 is a low 0.377 (benchmark value is 1), which suggest that India has a substantial sustainability gap to bridge.

The approach and the results imply that India or any other emerging/developing country needs to have a serious relook at (i) the goals and targets set for the electricity system, (ii) the set of prioritized technology and policy interventions, and (iii) the models and approaches adopted for strategic electricity planning. The findings from our research clearly indicate that countries like India need to adopt “minimizing sustainability gap” rather than “increasing GDP growth” as the sole criterion for deciding about the challenges raised above for the electricity system. We strongly believe that this approach will not only meet the economic development objective set for the electricity system but also help achieving the societal aspirations as well as environmental compliance.

We establish that Indian electricity system is poised for an imminent transition into a sustainable system. What constitutes the inputs, the processes and the outcomes of this transition are of immense interest and have been widely debated in the literature. We motivate and implement an electricity system generation expansion model with multi-attribute technology characterization to model the sustainability transition of electricity system and understand the feasibility, cost and carbon emission implications of generation augmentation. We build on the state of the art resource and technology characterization. We obtain the expansion planning requirements for Indian electricity system by superimposing the projected incremental increase in demand with the retirement schedule. Further,
building on the recent advances in power system modelling, we formulate the electricity system transition problem as a grouped integer generation scheduling and generation expansion planning model. This formulation accounts for plant startups, minimum loads, operating reserves, ramping limits and plant life. We run multiple experiments by varying the system configurations for a planning horizon of 18 years till 2032 and characterize the system on select indicators under three dimensions of sustainability for each year. Within the select scenarios, NESSI value in the terminal year varies from 0.481 to 0.51 relative to the base year value of 0.377. We throw some light on how the important questions concerning technology pathways for electricity system sustainability transition can be queried.

The approach adopted for this research is two pronged. First is to formulate and subsequently answer the question: What is and what should be the electricity system of India? The second is to answer: what are the prospects for transition of electricity system into a sustainable state? How do probable technology pathways manifest in terms of national electricity system? Can renewable energy deliver? Our proposition—which we validate through this research— is to formulate and subsequently answer the questions in two phases. The two phases are briefly detailed below:

In the first phase, the question we have attempted to first formulate and subsequently answer is: what is and what should be the electricity system for India? We propose to employ an indicator based approach for this part of the research, which attempts to evaluate India’s electricity system using the sustainability framework. The analysis of the indicators belonging to economic, social, environmental and institutional dimensions of sustainability will provide a deeper understanding of the system, identify and quantify the prevailing sustainability gaps and develop specific targets for interventions.

We begin with a survey of literature in the domain of sustainability assessment. We identify and briefly discuss the essential concepts, ideas and methods used in sustainability assessment. We observe the emergence of electricity related concerns in the wider sustainability discourse.

Next, we survey the literature on electricity systems and discuss the intersection of energy systems with development. Than we define the sustainable national electricity system and bring out the synergies between measurement of sustainable development and assessment of objectives of electricity systems. We observe cross country variations in electricity system planning objectives. While focus for developed nations has historically been economic and has subsequently included environmental concerns of climate change and pollution. In addition to economic and environmental aspects, the low
levels of access as well as consumption are a reality for India and other developing nations. This adds another dimension to the status assessment and subsequent planning of national electricity system of India.

Synthesis of sustainability assessment and objectives of electricity system planning in this phase culminates with conception and evaluation of National Electricity System Sustainability Index (NESSI) for India. The underlying theme throughout this phase is our attempt to first formulate and subsequently answer: What is and what should be the electricity system for India?

In the second phase, a modeling approach has been developed to optimally prioritize the interventions (energy-technology supply chains) in response to the specific targets (from Phase 1) for planning a sustainable electricity system for India. All the possible supply chain interventions tracking the transitions from energy resources to electricity in the bus bar on grid (as modeled by a Reference Energy System) form the inputs for the mathematical model. The output is the optimal set of interventions as trade-off solutions, which meet the targets set by the sustainability goal. The criteria like cost, efficiency of transformation, emission coefficients and energy resource availability form the basis for developing the optimal plan.

We begin this phase with survey of literature on power system modelling. Electricity system planning has been undertaken in academic and planning domains for several decades. It is only recent that, driven by the imminent challenges of de-carbonization, affordability, equity and security- which has resulted in coevolution of several possible technological, behavioral and policy intervention proposals- there is demand for coherent assessment of these propositions for electricity system transition. In our work, we have focused on supply side technology interventions.

Supply side technology intervention propositions for electricity system transition more often than not involve variable renewable energy, i.e., solar and wind. Variable renewable energy technologies pose significant modelling challenges because of their characteristic intermittency which induces complex dynamics in the complimentary system, i.e., electricity generating technologies other than renewable energy. We identify tremendous activity in the domain of electricity system modelling with focus on model representation of electricity system constituents which has significant implications for the outcomes of the planning exercises undertaken with these models.

Literature synthesis in this phase culminates with our attempt at mathematical modelling of generation technology pathways for electricity system in transition. Undertaking this exercise has involved
preparation of model feeds: energy resource supply profiles, generation technology specifications and demand projections.

We have done a series of numerical experiments to establish validity of the model. Subsequently we have validated various scenarios for Indian electricity system representing different levels of transitions, which provides insights which we expect will be useful for the stakeholders. The underlying theme throughout this phase is our attempt to answer the questions: How does one understand electricity system transition? How do electricity generating technologies interact amongst each other to yield certain set of system outputs? Can renewable energy deliver?

In our pursuit of finding answers to several questions raised at various points in this thesis and alluded to above, we have done a systematic systemic diagnosis of Indian electricity system. We have developed a multi-dimensional and multi-hierarchical indicator based framework to measure national electricity system sustainability. We have assessed Indian electricity system with this framework, to understand if Indian electricity system is sustainable and how it can transition towards a more sustainable state. Based on this understanding, we have investigated electricity generation technology pathways for a transitioning electricity system. We have modelled India as a single region with aggregate temporal profiles of resource availability and hourly loads. Building on the recent literature on power system modelling and their application, this thesis is a systematic exposition of how the important questions of supply side technology portfolio concerning electricity system sustainability transition can be queried. The results are based on several instances of data inputs.

Main contributions from our work are:

1. Introducing the concept of sustainability of national electricity system and defining it comprehensively for the first time.

2. Conceptualizing, developing and validating a multi-dimensional and multi-hierarchical indicator-based framework for assessing and benchmarking national electricity system sustainability. This framework is generalizable and applicable to the electricity systems of all the countries for assessing the sustainability status.

3. A composite measure of National Electricity System Sustainability Index (NESSI), which can be used to identify and quantify prevailing sustainability gaps in the national electricity system and
provide a goal for sustainability transition of the electricity system through higher NESSI target values. The constituents (dimensions, themes and indicators) of NESSI can enable identification of interventions and fixing of targets for such a transition.

4. Conceptualized, developed and validated an integrated mathematical model of generation expansion planning (supply augmentation) and generation scheduling with extensive operational details for electricity system in transition. This included:

- Enumeration and characterization of reference electricity system (energy resources, electricity generating technologies and demand for electricity).

- Demand profiling which involved estimating annual peak demand and demand for electricity, consideration of annual retiring capacity and computation of representative demand profiles (load curves) for past and future years using time-series load data.

- Modelling variable renewable energy (wind, solar and hydro) by developing representative energy resource availability profiles using time-series data.

- Harmonizing the extracted temporal energy resource availability and load profiles to preserve the chronological correlations.

- Explicit modelling of capacity utilization by proposing and implementing unit profile inversion. Effectively, it implies that generation from the variable generation capacity, e.g., solar capacity is upper bounded by the representative profile corresponding to that capacity.

- Optimally selected generation technology interventions for planning sustainable electricity system for India under select scenarios.

5. Juxtaposition of indicator-based macro model of electricity system sustainability assessment with bottom-up mathematical model of generation expansion planning and generation scheduling to evaluate official Indian scenarios of electricity system planning for sustainability transition.
In summary, we have developed and demonstrated an empirical instance of an integrated methodology, beginning from a systematic diagnosis of the national electricity system to a meaningful solution. Through this thesis, we have attempted to understand the alternate future electricity supply transitions, their implications for society and environment and how they are influenced by the planning decisions.

In conclusion, there is substantial activity in all stakeholder domains: research activity, actions by NGOs and the government but given the long term nature of probable interventions, sustained efforts will be required to reach the desired outcomes. Future of grid is the biggest system level problem, which we believe we have illuminated to some extent and which could benefit from further research. While planning exercises using complex models are useful in their own right given the complexities of real world close monitoring and scrutiny of the evolving electricity system and timely course corrections will be critical