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A Pitfall in Pathways for Energy Transition: Underestimated Value of Long-Term High-Resolution Electricity Demand Projection

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Abstract:

The importance of long-term high-resolution electricity demand projection has long been neglected. Given that the reliability of the electric power sector depends on a perfect balance of demand and supply at different time scales, projecting the temporal load shape and peak consumption is of paramount importance for the system's capacity planning processes. Without projecting long-term (up to mid-century 2050 or longer) electricity demand at a high temporal resolution (at the hourly or sub-hourly level), it is impossible to devise effective strategies for energy transition, including integration of renewable energy, deployment of distributed energy resources and energy storage systems, improvement of end-use energy efficiency, and demand-side management. Climate change and the emergence of electric vehicles, which will drive up fluctuations of electricity demand, will make these strategies even more difficult to devise. The authors propose a roadmap to develop a bottom-up modeling tool that is capable of producing long-term high-resolution demand projections, with the incorporation of demography, building science, engineering, meteorological knowledge, and behavioral science.

Keywords:

Electricity Demand, Energy Transition, High-resolution Projection, Energy Planning

1. Introduction

The decisions made today about the electric power sector will have profound and long-lasting implications not only for the economic and social well-being of citizens, but also for the state of our natural environment [1,2,3,4]. Long-term electricity demand projection is crucial for electricity planning, since meeting electricity demand often requires irreversible investments in expensive and long-term infrastructure. It may take years to design and implement this infrastructure, and this temporal investment acts as a constraint on future choices [5].

Therefore, electricity demand projection enjoys enduring popularity in both academia and the industry [6]. Nevertheless, the topic of long-term (up to mid-century 2050 or longer) high-resolution (at the hourly or sub-hourly level) electricity demand projection is rarely investigated in depth. Different from other energy sources, such as coal or natural gas, electricity must have a perfect balance of demand and supply at different time scales to ensure the reliability of the electric power sector. Given this, projecting the temporal load shape and peak consumption is of paramount importance for the system's capacity planning processes. Nowadays, with new trends like the increasing penetration of renewable energies, climate change, and the adoption of electric vehicles, this long-term high-resolution demand projection is more necessary than ever, especially in many developing countries where load profiles will fluctuate more and more in the future.

For years, electricity demand projections have been supported by bottom-up modelling tools like the Long-range Energy Alternatives Planning System (LEAP) and the National Energy Modelling System (NEMS). These tools have facilitated the planning of electrical systems by providing recommendations regarding economic and environmental aspects. In addition, some top-down models have been widely discussed and applied in industry to project electricity demand by associating electricity consumption with economic, demographic [7], and weather indicators [8]. Although both kinds of modelling tools provide fundamental insights that support the power systems planning process, they fail to fully reflect the variability of the electricity demand since their projections are made on a yearly basis. Some research has focused on high-resolution demand projections, but only as applied to short time scales, such as day-ahead projections [9]. Therefore, existing research, either failing to reflect the variability of future electricity demand, or lacking long-term projection, cannot provide useful guidelines for long-term power planning.

Electricity demand will present increasing fluctuations with aggressive electrifications and estimates of future electricity demand that are useful must provide information at an hourly or even intra-hourly resolution. Thus far, the penetration of appliances is far from saturated, but there will be a dramatic increase in this penetration over the coming years, especially in the residential sector of developing countries [10]. Also, some new end-uses like transportation via electric vehicles will experience a sharp rise [11]. Further penetration of these electric appliances, compounded with higher usage fluctuations associated with extreme temperatures [12], will contribute to sharp variations in electricity consumption. If these increasing fluctuations are not carefully reflected in the projection of future electricity demand, a robust and efficient planning of the infrastructure that is required to generate, transmit, and distribute electrical power will not be achievable. As a result, the planning of electricity capacity may fail due to overcapacity or insufficient capacity.

This paper contributes to the understanding of long-term high-resolution electricity demand projection in two ways: 1) it highlights the significance of projecting long-term high-resolution electricity demand in devising effective strategies for emerging energy transition; 2) it proposes a bottom-up framework for long-term high-resolution demand projections, which can be used in further research.

2. Significance of Long-term High-resolution Electricity Demand Projection in Energy Transition

Existing research in designing future electric power system neglects the change in variability of future electricity demand, inevitably risks the reliability of the electric power sector. Only by projecting future electricity demand at a long-term high resolution, will we be able to devise effective strategies for emerging energy transition, such as the development of renewable energy, distributed energy resources, energy storage systems, end-use energy efficiency measures, and demand-side management and response (Figure 1).

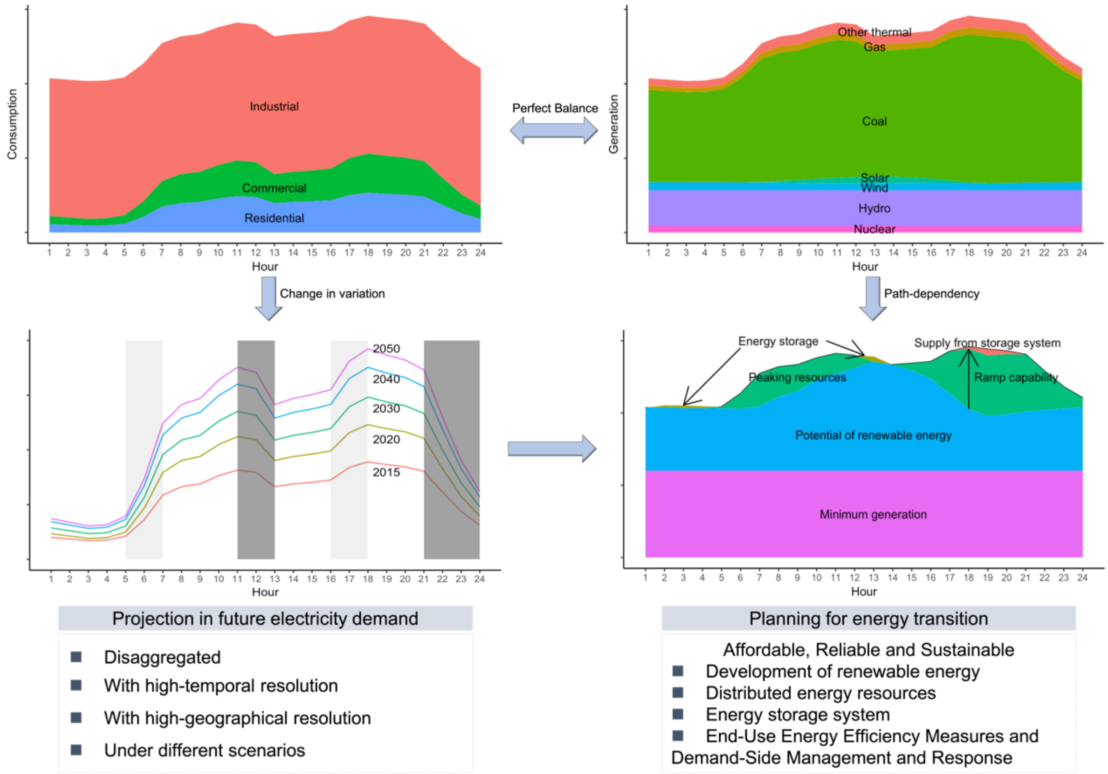

Figure 1. *Schematic figure of projecting future electricity demand at a long-term high resolution and devising effective strategies for emerging energy transition.*

2.1. Electricity System Planning with Penetration of Renewable Energy

Renewable energy development has become a tendency in energy transition, and leading countries like China have set ambitious targets for renewable energy development. In this regard, some studies have examined the long-term potential of renewable energy integration, accounting for the variability of weather and its corresponding influence on renewable energy resource supply curve, and the high-resolution load curve of specific target years [13,14,15,16,17]. Some research has argued that a renewable energy supply that relies solely on wind, solar, and hydro energies can be achieved [18,19,20,21], while other research has debated these claims [22].

The aforementioned research has supported the development of high-fidelity models for forecasting renewable power integration and integrated resource planning. Nevertheless, the processing methods commonly used for the computation of long-term consumption projections are vague and generally assume that the shape of the load profile remains identical to the base year. These methods also scale the target year according to annual electricity demand growth projections.

Realistically, the shape of load profile changes from year to year; as such, the aforementioned methods produce inaccurate calculations of the real potential of renewable energy sources that could be effectively integrated into the grid. Specifically, these inaccuracies are the result of the discrepancy between the shape of the load profile and the shape of the renewable generation curve. For example, the peak electricity demand occurs in the afternoon, while the peak generation of solar power occurs at around noon. Therefore, the increasing fluctuations of electricity demand reduce the potential for solar energy to integrate into the grid and making the previous estimation about solar integration inaccurate. Therefore, the outcomes of underestimating the variation of future electric load are overly optimistic estimations of renewable energy integration potential and risks to the reliability of the electricity supply.

A key prerequisite for meaningful research that can accurately guide the development of the power generation portfolio and provide useful perspectives on economic, reliable, and low-carbon power planning is to develop a fidelity method that can investigate the changing variation of electricity demand at a high resolution in the long run.

2.2. Development of Distributed Energy Resources

Long-term high-resolution electricity demand projections also play an important role in the analysis of distributed energy resources and their interaction with centralized power systems. Distributed energy resources can make full use of dispersed energy resources, such as solar and wind energy, small hydro turbines, Combined Heat Power (CHP) based microturbines, and are viewed as an important and cost-effective means of developing efficient power systems [23,24,25]. Nonetheless, they carry with them drawbacks to power systems, including limited generation and reserve capacities in meeting local demand [26]. Some studies analyzing the optimal planning and operation of distributed energy resources considered the variation of current electricity demand, but failed in considering the increasing variation of future electricity demand and its implications in the development of distributed energy resources [27,28].

The limitations of distributed energy resources will become more acute as the fluctuations in electricity demand rise, exceeding the response capacity of these resources. As a result, the performance of the grid will rely more on centralized power systems, especially at peak load hours during hot summer and cold winter months. Future electricity demand projection at a high resolution can provide necessary information for utilization planning of distributed energy resources, while avoiding reliability issues of energy system.

2.3. Development of Energy Storage Systems

Along with the integration of intermittent renewable energy sources, distributed systems, and the drastic fluctuation of energy demand, energy storage will become more attractive to stakeholders. It is expected that energy storage will play a vital role in harmonizing unexpected variations between renewable energy generation and electricity demand [29, 30]. In addition to the research in energy storage technology, investors and policy makers require a clearer performance evaluation and a robust financial assessment to persuade them to increase investment and encourage public policies in favor of energy storage technologies [31,32,33]. Without accurate, detailed and tunable projections of future demand profile, these evaluations and assessments are not convincing.

Current research on the value assessment of energy storage has been largely focused on its relationship with the development of wind and solar energy [34,35]. It has rarely discussed the impact of electricity demand fluctuations on the grid, such as the effects on the reliability of electricity supply or the risks associated with electricity generation costs, mainly at peak demand. When these issues are analyzed, additional benefits of implementing energy storage are revealed. The development of energy storage systems is crucial not only to avoid the curtailment of renewable energy at base load, but also to act as a substitution of peak load power generation plants. What is more, the flexibility of energy storage systems can provide enough ramping capabilities to guarantee the reliability of power systems. Previous research has already demonstrated the value of energy storage in lowering electricity generation costs, improving the reliability of the grid, and reducing the environmental impact of electric generation systems. But, as previously mentioned, without considering the rising fluctuations of electricity demand, the value of energy storage systems may be underestimated. The information required to fully assess the market potential, environmental impact, and economic profitability of energy storage systems can only be made available by projecting future electricity demand at high resolution.

2.4. Synergy between Research in End-Use Energy Efficiency Measures and Demand-Side Management and Response

A cost-effective way to guarantee the provision of reliable, affordable, clean electricity services is end-use energy efficiency improvement. The importance of improvements to energy efficiency will become more salient when considering the further adoption of appliances [36] and the lock-in effect during their life expectations. Thus, the evaluation of related policy design in energy efficiency improvement should take long-term demand projection into consideration. Characterizing possible futures of each end-use at a high temporal resolution that takes into account the uncertainties about energy efficiency can provide vital guidelines for prioritized appliance and related technology selection in energy efficiency improvement and optimal design and implementation of end-use energy efficiency measures.

Demand-side management and response is another viable alternative for achieving a reliable energy supply by modulating fluctuating demand through measures like valley filling, peak shaving, and load shifting [37]. The energy management system for Smart Home, which can control the usage of specific appliances like electrical water heater and HVAC (heating, ventilation, and air conditioning) system without compromising the comfort of residents, is becoming a promising measure of demand-side management and response [38,39,40,41,42]. Along with the increasing fluctuations in future electricity demand, demand-side management and response will become a more indispensable measure, especially in a prosumer era in which electricity consumers actively participate in electricity trading and respond to price changes [43]. However, not all end-uses are available for demand-side management and response at a short time-scale, Therefore, a reasonable design of a demand-side management and response system that takes into account which, when, and to what extent end-uses can be managed requires a comprehensive knowledge of future demand at a high temporal resolution. This knowledge should incorporate a detailed characterization of the components of end-use electricity demand and their load profiles.

3. Obstacles and Roadmap

In view of the significance of that which is described above, the authors strongly believe that research on long-term high-resolution demand projection is imperative to step to the possible future of electric power systems. Due to the unique usage pattern of each end-use, this is only achievable by developing a bottom-up modelling tool through an information-driven analysis that identifies the contribution of each end-use towards the aggregate electricity consumption. Particularly, the proposed modelling tool should be one that facilitates the consideration of uncertainties about demographic change, saturations of various end-uses, energy efficiency improvements, building additions, diverse usage patterns, and climate conditions.

Research of this type is challenging to carry out in practice. Not only does it need to identify the massive amounts of economic, social, meteorological, technological, and policy factors that affect electricity demand, but it must also analyze the complex mechanisms that affect several components of high resolution electricity consumption in residential, commercial, industrial, and emerging transportation sectors. Therefore, this research requires an understanding of electricity systems, environmental science, and social science, in combination with technical skills in economics, statistics, engineering, geographic information, and computer science.

Another significant obstacle for high-resolution electricity demand projection is the lack of available data. To obtain the data required for this research, it is necessary to apply survey instruments to gather first-hand information on usage patterns of end-uses, as well as attitudes and behaviors that affect future electricity consumption. In addition, it is necessary to install an advanced metering infrastructure to collect information on the ownership and use of electrical appliances. Behavioral research on energy consumption should also be conducted to project possible changes in technologies, socio-economic conditions, regulatory framework, and consumers' behavioral trends.

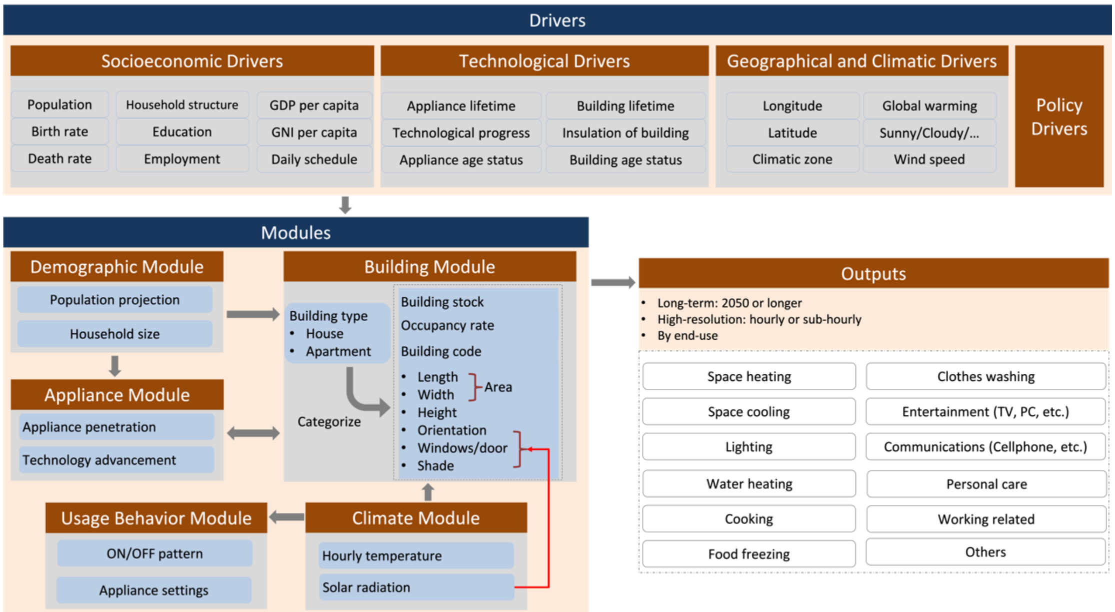

Figure 2. *Summary of the proposed bottom-up framework for residential sector.*

Here the authors propose a framework to build a bottom-up model for long-term high-resolution demand projection. Despite the differences in electricity demand between the energy consumption sectors, the residential sector often sets the magnitude and timing of peak consumption and causes the majority of temporal fluctuations. Hence, the framework here focuses on the analysis of demand in the residential sector, but with appropriate adjustments, it could also be applied to other demand sectors including industrial, commercial and transportation sector. Therefore, we could get a full profile of electricity demand. The proposed framework is made up of five modules that consider demographics, appliances, dwellings, climate and usage behaviors (Figure 2).

3.1. Demographic Module

The demographic module aims to understand future population growth and evolvement of household size. Population is the base unit of measure of the end users, and a household is the minimum entity of residential electricity consumption. Understanding the possible futures of the number of households would lay a solid foundation for the electricity demand projection. Demographers are already equipped with such methodology to conduct this type of long-term projection, and this methodology should be adapted to research in residential electricity consumption projection.

3.2. Appliance Module

After understanding who consumes electricity, the next step is understanding the type and number of appliances people use in their households. To do so, the household appliance module includes two main submodules: the appliance penetration submodule and the technology advancement submodule.

The appliance penetration submodule relates income growth [36] and other indicators to determine how much any specific type of appliance is used in a household. This submodule should incorporate economic and social knowledge, and employ econometric methods to delve into the determinants of each household appliance. It needs to be emphasized in particular that space heating and cooling are major energy consuming end-uses of the residential sector, and the penetration of electric appliance for space heating and cooling attributing to economic, social, and policy drivers should be focused on. It also needs to be noted that penetration of electric appliance may be affected by emerging energy technology. For example, household may substitute coal or natural gas with electric equipment along with the installation of solar PV panels in residential rooftop.

The technology advancement submodule aims at understanding the future energy performance of each appliance with emphasis on the replacement of existing equipment and energy efficiency improvement of new equipment. For this task, a system dynamics technique, which incorporates technical factors, expected life-time features, and technological progress, should be used to understand the likely outlook of energy efficiency.

3.3. Building Module

Different dwelling archetypes, such as houses and apartments, exhibit different types of electricity consumption [44]. Factors related to building stock, building age status, building area, height, surface thermal insulation, orientation, fenestration, or even shading influence the energy consumption of each type of residential building. In this regard, the residential building module aims to understand the current conditions of residential buildings by considering the factors mentioned above in addition to the socioeconomic factors that influence the way dwellings are newly built, renovated, or removed. This module produces projections of future residential buildings by assuming different scenarios of changes in determinants. Building science should be integrated into this research to support the analysis of the way residential dwellings may be built and managed in the future.

3.4. Climate Module

Climate factors such as temperature should be incorporated into electricity consumption analysis, since temperature is a crucial determinant for space heating and cooling analysis. More importantly, extreme temperatures are becoming more frequent, aggravating the temporal variation of electricity demand. Also, electricity consumption from lighting is closely correlated to weather conditions (sunny days, cloudy days, or others). In this regard, the climate module aims to understand and project climate factors that directly or indirectly affect electricity consumption at high resolution. This module should take as key inputs the different scenarios of future temperature changes obtained from the forecasting models of climate science. In addition, many projections about future climate changes from geographic science should be incorporated to enable the analysis of outdoor weather conditions and solar radiation. Based on this analysis, we expect to have a better understanding of how climate conditions affect indoor climates where people use most of their appliances.

3.5. Usage Behavior Module

The usage pattern of each residential end-use is the primary source of electricity demand variation. Due to the unique usage pattern of each appliance, each end-use presents a different load profile [37]. Therefore, an accurate analysis of future demand variation must account for these differences. As such, the usage behavior module aims to understand the various usage behaviors of each end-use at a household level and to discover their typical usage patterns. However, such behavioral information is difficult to examine since households with different life-styles may have different behavioral patterns for the same end-use. To collect the data required for this analysis, primary collection methods like surveys and interviews should be used. In addition, classification techniques such as hierarchical methods should be applied to categorize household behaviors into several typical usage patterns for each end-use. Finally, the projection of usage behaviors should be done for each category. We believe many behaviors should be consistent over such a long time, for example, human would still feel not comfortable at 30^{o}C in the future. Therefore, the present behaviors collected and analyzed could be useful in the future. It needs to be noted that the usage behaviors of space heating and cooling equipment are closely correlated with weather conditions, and the information of equipment settings and climatic conditions should be combined together to understand residential usage behaviors.

4. Discussions

The authors feel confident that a framework that includes the five modules described above will produce reliable long-term high-resolution electricity demand projections in the residential sector. In particular, the long-term high-resolution electricity demand projections can be a set of scenarios that combines the uncertainties of many drivers, such as population change, income growth, technological improvement, variability of weather, and usage behavior. Such tunability is much superior to the top-down model when dealing with variability in electricity demand and could help us catch more truth of the future when we know future better, by adjusting the variables. Also, by capturing typical weather conditions and usage behaviors for one week in each season, these projections can be hourly (or sub-hourly) load profiles for a typical week in each season of each year.

The authors also believe that, with some adjustments, this approach can be used to project electricity demand in the industrial, commercial, and transportation sectors. For example, by focusing building analysis with factories, adjusting demographic module to project future industry participants, replacing appliances with industrial equipment, and changing behavior patterns with production schedules, it would be possible to project demand for the industrial sector. Also, by replacing residential electric appliances with electric vehicles, and behavior patterns with charging behaviors, and some other adjustments, it would be possible to project demand for the transportation sector.

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5. Conclusions

The importance of electricity demand projection at a long-term high-resolution has long been neglected. Without projecting future electricity demand at a high temporal resolution, the optimal trajectory of electricity capacity expansion may not be achievable. At present, trends like climate change and the integration of electric vehicles are driving up fluctuations in electricity demand, and long-term high-temporal resolution demand forecasting is becoming more and more crucial.

As such, the authors strongly believe that the research on long-term (up to mid-century 2050 or longer) high-resolution (at the hourly or sub-hourly level) demand projection is imperative, and a bottom-up modeling tool should be developed with an information-driven analysis for high-resolution electricity demand projection. This research for the first time points out the importance of long-term high-resolution electricity demand projection in devising effective strategies for emerging energy transition, such as the penetration of renewable energy, development of distributed energy resources, energy storage system, end-use energy efficiency measures, and demand side management and response. This research elaborates biases existing research has in robust and efficient planning of electrical power infrastructure without a careful projection of future electricity demand at a high-resolution. This analysis enlightens the research in planning for future electricity system, and provides support for policy making in energy transition, environmental protection, and public engagement.

This research discusses the obstacles that will be met in high-resolution electricity demand projection, and provides directions for projecting future electricity demand at a high temporal resolution. The proposed bottom-up framework would provide guidelines for future research, and allow electric system planners to extract at least the following four pieces of information required for planning the expansion of the capacity of power systems: 1) magnitude and timing of the expected peak load; 2) magnitude and timing of the largest ramping or step-change in load; 3) magnitude and timing of the minimum load of the year; and 4) load duration curve (i.e. the length of time the system is at each load level). This information is crucial for designing strategies that support energy transition policies that ensure the future reliability, economic feasibility, and environmental sustainability of the grid.

Conflicts of Interest

The authors declare that there is no conflict of interest regarding the publication of this article.

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