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Infrastructure Modeling Methods: Review and Use Case Analysis.

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Abstract

Infrastructure is one of the crucial components of any economy, and its development can serve purposes beyond economic expansion. Investments in infrastructure can be directed towards advancing social fairness, protecting the environment, enhancing public health, pursuing political objectives, or even personal enrichment. In the absence of any benchmark, particularly about future demand, determining the optimal location, kind, and magnitude of infrastructure projects can pose a challenge. In recent years, various models have been developed to estimate infrastructure demand, cost associated, and investment needs. The present work seeks to answer this issue by synthesizing findings from the research on models used for infrastructure estimates found in the existing literature and categories into three main types of models, bottom-up, top-down, and hybrid, based on various assumptions of price, technology, demand, climate change, climate policy, and other significant issues. These models serve the purpose of providing valuable insights to guide policy decisions. The study shows that no specific model is perfect for estimating infrastructure needs. However, the hybrid model is more comprehensive and provides better results.

Keywords: Infrastructure Development, Bottom-up Models, Top-down model, Hybrid Model, Infrastructure projections, Modelling methods

1. INTRODUCTION

1.1. Role of infrastructure in development:

The infrastructure of an economy is crucial for its advancement and future development (Schwab, 2018). Infrastructure availability facilitates the delivery of necessities, driving economic growth, reducing poverty, and promoting environmental sustainability (Adshead et al., 2019). Infrastructure is a necessary factor for economic development through direct or indirect contribution. Infrastructure sub-sectors such as urbanization, transportation, and ICT are vital for long-term economic growth (Pradhan et al., 2021). The development of a country is aided by the infrastructure that provides services to the masses, production factors, and society. The quality of life of people, especially those from lower-income groups, is greatly influenced by the availability of infrastructure facilities such as clean water supply, proper housing, sanitation facilities, transportation, electricity, and communication. Other important social sectors, such as education and healthcare, are vital in providing amenities like toilets and improving the overall quality of life (Grum & Kobal, 2020). Infrastructure facilities are considered an integral part of the factors of production for suppliers of goods and services, goods carriers, and transactions related to goods. This encourages lower costs and leads to more growth, which boosts incomes and lowers poverty (Chotia & Rao, 2017). Investing in quality infrastructure is crucial in mitigating climate-related risks and disasters (Satterthwaite et al., 2020; Lu, 2019). The lack of availability of infrastructure is mainly recognized as the primary constraint to the growth and development of a nation (Ojah & Kodongo, 2017). Development policies for the infrastructure growth model and particularly organizing funds for investment in infrastructure have been the biggest challenge in developing economies (Ehlers, 2014).

At the macroeconomic level, the impact of infrastructure on output, growth, and productivity has been extensively studied. Since the publication of Aschauer's (1989) fundamental study, several articles on this topic have been produced, and as a result, the body of relevant research has grown substantially over the last two decades or more. The research investigation has used various data sources, empirical approaches, and infrastructure-related tools. Most of the research suggested that infrastructure has a beneficial long-term impact on economic growth and productivity. Further, a few other studies indicate that physical and human capital infrastructure investments enhance productivity, reduce transaction costs, and improve economic performance in various contexts. Many studies emphasize the crucial role of infrastructure development in fostering economic growth, thereby contributing to social welfare improvements in societies. Using the US-stated data, Garcia-Mila and McGuire (1992) pointed out that highways and schools are two inputs that significantly boost productivity. Similarly, in their study of Sub-Saharan African countries, Estache, Speciale, and Veredas (2005) also reported strong statistical evidence that sub-sectors of infrastructure (telecom, roads, electricity, and water) contribute significantly to economic growth.

Studies have also found a connection between infrastructure and development at regional, national, sub-national, and multi-country levels (e.g. Sahoo & Dash, 2009; Shi, Guo, & Sun, 2017)). Investment made in infrastructure has a direct and considerable impact on development in India, according to Sahoo and Dash's (2009) interpretation of the connection between investment in infrastructure and development at the national level. The contribution of infrastructure to the growth of the manufacturing and industrial sectors has been the focus of several studies looking at the relationship between infrastructure and development in the Indian context (Mitra et al., 2012).

The Government of India (GoI) has undertaken various steps to promote economic growth through infrastructure investment. These initiatives aim to improve infrastructure quality, attract investments, and foster sustainable development. The Government in India, over the years, has promoted and provided a positive environment for the private sector to develop partnerships with the public and private sectors (NIP, 2019). The National Infrastructure Pipeline and National Monetization program are growing in that direction. To achieve its goal of a USD 5 trillion economy by 2025, India needs to invest in various sectors and promote growth and development. This requires resilient investment in different types of infrastructure (PIB, 2018) with constant government intervention (Adshead et al., 2019), robust funding, and continuous project monitoring (Delmon, 2021). Factors such as fast-increasing urbanization, an increase in the working-age population, and a change in global climate (Kumar et al., 2021) all necessitate more investment in India's infrastructure sector.

1.2. Infrastructure Models:

Infrastructure development and maintenance play a crucial role in facilitating economic output, promoting commerce, and enhancing the quality of everyday living. Significant relationships exist between infrastructure and development, including reduced poverty and employment (Malah Kuete & Asongu, 2023). Estimating infrastructure needs is crucial for planning, developing, and maintaining various forms of infrastructure for numerous reasons, including optimal allocation of resources, sustainable growth, quality of infrastructure, environmental impact, energy efficiency, technological advancement, land use, safety, disaster management, etc. The estimation provides an initial step toward achieving development through informed decision-making, strategic planning, and sustainable development. By adopting these strategies and policies, countries can harness the potential of infrastructure to drive economic development, elevate living standards, and achieve inclusive and sustainable growth. Estimating infrastructure needs is a systematic way to examine and quantify infrastructure development, upgrade, and maintenance needs. This multistep approach starts with identifying objectives, which is not limited to how much investment is needed to achieve a particular level of infrastructure but is also accompanied by social, economic, and environmental objectives. Thus, this research paper is not limited to the models used to estimate investment needs but also to the cost associated, technological advances, climate goals, etc., that contribute to infrastructure needs. In the literature, words like “needs,” “demand,” “requirement,” and “Gap” have all been used interchangeably. Studies by Fay and Yepes (2003), Bhattacharya, Oppenheim, and Stern (2015), and Adshead et al. (2019) emphasize the significance of estimation of investment needs in infrastructure to achieve sustainable development. The quantity required is contingent upon the goal being pursued, which is determined by individual nations’ social and environmental objectives, economic development aspirations, and contextual factors.

Various estimates have been made for infrastructure requirements using different methods to achieve global or national objectives. However, challenges have arisen while estimating demand for infrastructure using different methodologies and comparing the results. These estimates indicate a significant gap between the projected requirement and the availability of infrastructure stocks in the future.

This study has examined different approaches adopted by global economies and relevant studies for estimating the infrastructure. Based on the literature review, methodologies for infrastructure demand are grouped into three models: bottom-up (focusing on project-level or microeconomic modeling), top-down (focusing on national-level investment needs using econometric or macroeconomic models), and a hybrid that combines both methods (as illustrated in Figure-1).

Figure 1: Different Approaches for Infrastructure Modeling

The study consists of eight sections. Section 2 reviews the literature on models, methods, and approaches used to estimate infrastructure, including the types of infrastructure and the sub-components of the methods. Sections 3 and 4 provide insights into the objectives and methodology of the study, respectively. Section 5 presents data analysis and interpretation, while section 6 includes a discussion. Concluding remarks are offered in section 7, with suggestions provided in section 8. Lastly, section 9 outlines the limitations of the study.

2. REVIEW OF LITERATURE

Over the years, various estimations of the infrastructure needed for different goals have been made using various assumptions and approaches. Adopting multiple assumptions, for example, future demand for infrastructure, estimated growth, population expansion, and increase in the rate of urbanization, are some of the key parameters used (Branchoux et al., 2018). In a few cases, the estimation was further translated into the investment needed to achieve the desired level of infrastructure. For example, as per the infrastructure report (World Bank, 2015) by the World Economic Forum (WEF), the total infrastructure deficit of the world will increase, and to fill this deficit, USD 20 billion per annum is required over the next two decades. The McKinsey Global Institute projected in 2013 that the outlay in infrastructure till 2030 should require around USD 570-670 billion. According to recent reports, India will also need around INR 50 trillion for infrastructure to achieve goals related to sustainable development.
The differences in estimates between various studies related to the estimation are often due to variations in the definitions of infrastructure, different inclusions of sectors like energy and water supply, and variations in the level of detail considered. There are two popular models for estimating the impact of infrastructure-driven policies on development: bottom-up models and top-down models (Ruiz Nunez & Wei, 2015). These models are classified differently based on their characteristics. Bottom-up models focus on technology details, while top-down models consider a more comprehensive range of market dynamics. Combining the bottom-up and top-down models is defined as the hybrid model.

Various methods have been used to estimate infrastructure needs for different sectors using various objectives and assumptions, each with its own approach and data sources. Here is a summary of some of the literature:

Table1:

Year	Sector	Objective	Source
2003	Transport, electricity, water and sanitation, and Telecom	Estimate the change in demand for infrastructure services that will arise from the expected structural change and growth in income the world is expected to undergo.	Fay and Yepes (2003).
2006	Energy, transport, water, and telecommunications	Investment requirements by sector for a group of countries and then improving the econometric model to determine aggregate spending needs.	OECD (2006)
2010	Energy, transport, water supply and sanitation, and ICT.	Local data for microeconomic models and spatial analysis, including the supply side variable to provide country-level development targets.	AICD (2010)
2013	Telecom, water, power, airports, ports, rail, and roads	The report uses a hybrid approach that combines both top-down and bottom-up methods to arrive at its estimates of needed infrastructure investments.	McKinsey Global Institute (2013)
2014	Transport, communications, buildings, energy, water, and waste management	This study presents a detailed estimation of the global investment needs for sustainable infrastructure from 2015-2030, including energy efficiency and primary energy production investments.	New Climate Economy Global Commission (2014)

2018	Transport, energy/electricity, ICT, and water supply and sanitation (WSS).	Framework for estimating the infrastructure financing needs by 2030, considering existing infrastructure gaps, growing demands for new infrastructure, and climate-related risks.	Fang & Wu (2018)
2019	Energy, agricultural, transportation, industry, and service sectors	Comprehensive and accurate assessment of the costs and benefits of climate change mitigation policies, compared to previous studies that relied on economic models alone	Fujimori et al. (2019)

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The researcher tried to analyze models used in the existing literature to estimate the infrastructure requirement. They were grouped into three models based on methodology, approach, and factors: bottom–up, top–down, and hybrid models. Based on the literature, it was observed that the broad factors (as mentioned in Table 2) may be categorized into three models.

Table 2: Categorization of the models based on factors.

Model for estimation	Broad Factors Considered under the Model
Bottom-up Model	Microeconomic model, micro-engineering models (detail analysis), investment demand at the project level, sector level (road density, rail density, supply of clean water, airports transportation, ports transportation, and economic corridors as well as oil and gas supply), investment demand, technological details.
Top-down Model	Macroeconomic models, universal estimation, estimation at the country level, estimation at the geographical level, estimation based on the income status of the countries, estimation based on the economic level of the countries, and estimation includes various market adjustments.
Hybrid Model	The amalgamation of both the models above is explained.

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2.1 BOTTOM-UP MODELS

The bottom-up model is a commonly used method for estimating infrastructure costs. The bottom-up method evaluates the total infrastructure economic demands at the project or microeconomic level (Wene, 1996). The bottom-up concepts are primarily determined based on individual project costs and demand in that sector (Kavgic et al., 2010). Bottom-up models provide detailed descriptions of technology but do not show how firms make microeconomic decisions when choosing technologies or potential macroeconomic equilibrium feedback.

The primary aims of bottom-up models often emphasize outcomes' responsiveness to the level of aspirations and the underlying assumptions of price, technology, demand, climate change, climate policy, and other pivotal variables (Conway et al., 2019). These models aim to provide insights that might facilitate informed decision-making in policy.

Further, using bottom-up engineering methods in the infrastructure sub-sectors, models use technological components and potential future developments are created in detail. These models examine how best to link up that requirement at the minimum possible price. The bottom-up models frequently respond in a binary manner, e.g., a minor variation in pricing may have no impact at all or cause significant variation in the combination of outcomes and inputs (Helgesen, 2013).

The majority of "Bottom-up" infrastructure models have been divided into a variety of models (Herbst et al., 2012):

- Optimisation models
- Simulation models
- Accounting models
- Multi-agent models

Optimization models are categorized based on their optimization technology and ability to identify the most cost-effective path in the overall system expenses. These models are also referred to as equilibrium (partial) models because they assist in balancing supply and demand in specific infrastructure stocks, such as IKARUS, TIMES-Norway, and TIMES-MARKAL models. Simulation models are a diverse group with varying modeling characteristics that depend on the optimization framework. They can involve the estimation of relations through econometrics. Large simulations may use optimization with different variables, some constant and others changing partially. They may also consist of multiple modules and features. Some commonly known simulation methods are Mesap-PlaNet and REMix. Accounting models, such as the MEAD model, are often applied with extrinsic presumptions for technological growth, making them less dynamic and not accounting for rates. The multi-agent models are a more comprehensive form of optimization models as they optimize different variables concurrently.

2.2 TOP-DOWN MODELS

The "Top-down" model generally evaluates the quantification of infrastructure demands at the country/regional level using econometric analysis. In the top-down approach, the relationship between infrastructure services is determined by establishing the demographic variable, which predicts the expected growth rate (Fay, 2001; Fay and Yepes, 2003). Once the assumptions of infrastructure stocks are decided, an internationally standardized cost of one unit is applied to arrive at the infrastructure demand in terms of currency (Branchoux et al., 2018). However, top-down projections generally depend upon past data for the countries where the model is used to estimate the demand based on the past, which is a significant predictor (Fay et al., 2011).
Top-down models differ from bottom-up models in that they address the limitations of bottom-up models by considering macroeconomic needs and estimating the changes that arise from introducing new technologies at the aggregate market level. This approach results in greater adaptability to changes in market dynamics.

"Top-down" models are generally categorized into four types (Herbst et al., 2012):

- Input-output models
- Econometric models
- Computable General Equilibrium models
- System dynamic models

Input-output models analyze financial flows across various sectors of the economy, including intermediate and end-use products (Ji, Zou & Tian, 2019). By examining these connections, one can estimate the financial effects of systemic changes in the economy. Econometric

models use time series analysis to study and identify the impact of various variables. This model establishes statistical relationships among economic variables to make assumptions about future projections based on the resulting model (Välilä, 2020).
CGE models, or computable general equilibrium models, are a type of microeconomic theory that determines how costs and actions in all sectors of an economy interact to reach an equilibrium (Manuel et al., 2021). CGE modeling also depends upon the data obtained at the national level, like in regional CGE. System dynamics have established rules for modeling factors, resulting in complex non-linear simulations (Pejic Bach et al., 2020). The two important models that use the top-down concept and provide the results related to the objective of considering the microeconomics approach are mentioned below.

2.2.1 Fay's Econometric Models

Fay's (2001) model aims to develop a framework for determining the necessary infrastructure levels as a consumer requirement and input for industrial processes. They created a model to forecast future infrastructure demand, and it works remarkably well across infrastructure sectors, including water and sanitation, road, rail, and power, where a lack of data typically makes estimation challenging. Demand estimates are used rather than a precise definition of "need." In addition, they predict the total amount of resources needed to meet new demand and maintain the service for existing stocks. They also estimate the resources required for maintenance based on the minimum amount of expenditure necessary to maintain the integrity of a system.

2.2.2 Computable general equilibrium (CGE) modeling

A system of equations known as a "Computable General Equilibrium" (CGE) model represents both macroeconomic limitations on the economy at large and the specific microeconomic behavior of interactions between its elements (Shahraki & Bachmann, 2018). The CGE model is an economic model that uses data to predict how the economy will respond to changes in technology, policy, or other external factors. This model consists of equations that describe the variables and a database that follows the model equations. The equations are typical of a neo-classical nature, frequently presuming that producers will operate in a cost-minimizing manner, that prices will be set at average costs, and that household demands will be based on optimal behavior (Niamir, Ivanova & Filatova, 2020).
A commonly adopted method for assessing infrastructure is using top-down models, such as a CGE model, which has been prevalent in the last few decades (Shahraki & Bachmann, 2018; Ishikura et al., 2020). Recently, the use of CGE models in regional policy research has increased. The go-to models for analyzing regional growth are the regional input-output and econometric models despite the rich original policy insights offered by regional CGE models.

Table 3: Example of Computable general equilibrium modeling adopted for infrastructure assessment.

S No	Sector	Major findings	Source
	Transportation	Applications of the Model used for spatial economics and interaction of transport.	Shahraki and Bachmann (2018)
	Economic policies	Regional economic development policies	Patridge and Rickman, (1998)
	Energy	Energy end-use technologies	Fujimori (2014)
	Hydropower	The development of projects related to large hydropower and its economic impact.	Hongzhen et al. (2022)

	Irrigation developments	Projections and assumptions on future irrigation developments	Wittwer et al., (2021)
	Air transport facility	Air transport projections and their investment	Forsyth et al. (2021)
	Agriculture expansion	Zambia's agricultural sector expansion	Mulanda and Punt (2021)
	Transport infrastructure	Belt and Road initiative	Chen and Li (2021)
	Economic reforms	Indian GST reforms and its projections	Bhattarai (2021)

CGE models with a top-down approach are flexible and innovative. They can be used to achieve various study objectives. In their study, Kuiper and van Tongeren (2004) developed a village-level model and utilized it to assess its macro-level impacts. Top-down regional CGE models' decreased data requirements, which mostly rely on secondary data sources, are its main advantage. Regional government microeconomic reforms, transportation policy, and similar affairs can be examined using customized versions of CGE models, like tax, trade, and environmental issues analyzed with regular CGE models (Madden & Giesecke, 2012).

2.3. HYBRID MODELS

The hybrid model blends bottom-up and top-down models, leveraging macroeconomic features with technological detail for precise and preferred projections. It is a well-researched approach with proven advantages. For example, Bohringer and Rutherford (2008) proposed that a hybrid model generally results in an integrated output for policy and decision-making. Hybrid models integrate the technological richness of bottom-up models and characteristics of top-down models of micro and macroeconomics to result in realistic projections (Jaccard, 2005). A hybrid model has recently become popular to estimate energy sector infrastructure needs. Mundaca et al. (2010) found that this model leads to a comprehensive improvement in evaluating energy efficiency. Hybrid models have evolved to combine the strengths of traditional top-down and bottom-up models by using a scientific approach to replicate end-user and producer actions. In a hybrid modeling approach, Rhodes et al. (2022), based on a base survey, compared the economy models for energy. They have discussed the comparative model with its implications for climate policy projections analysis and future research prospects. In their 2004 model, Nakata examined interlinkages between the energy system and the regional economy. The study compared microeconomics, macroeconomics, technology, policy representation, uncertainty handling, data transparency, and high-precision dimensional and material description.

To achieve a hybrid modeling architecture, Gupta et al. (2020) utilized a combination of top-down IMACLIM models and bottom-up AIM/End-use models of energy systems. The architecture relied on an original energy price dataset, considering national-level accounting and energy balance. The study aimed to evaluate the impact of low-carbon development pathways on the macroeconomics of a country like India. This study combines top-down (IMACLIM-IND) and bottom-up (AIM/End-use) models to assess the 2030 and 2050 projections of energy and economy in the Indian scenario.

TISMO, or Taiwan Integrated Sustainable Model, was developed and used for infrastructure and economic analysis policy simulation. TISMO shares similarities with hybrid models that use deep analysis to improve quantity and quality. TISMO follows a gentle methodology that connects both top-down and bottom-up models, making it useful for simulating policies and analyzing the economy as a hybrid model. As a result, hybrid models like TISMO can provide a better understanding of various improvements related to energy efficiency (Wu et al., 2019).

Another blueprint of the hybrid model is the Canadian Integrated Modelling System (CIMS) for energy. This model simulates the interaction between energy supply, demand, and macroeconomic performance indicators. Unlike most CGE models, it does not calibrate government budgets, employment, and investment (Rhodes et al., 2022). CIMS models simulate the progression of capital over time through withdrawals, replenishments, and acquisitions by end-users and producers with limited foresight. They consider the cost of energy at each energy service node of demand, such as heated areas of buildings or distance traveled. Stocks are removed in each period based on the dependent function of age and demand for new stocks. Their increase or decrease is determined by the initial extrinsic projections of the economy's output and the subsequent interaction of supply and demand and feedback between the energy sector and the rest of the economy. This model operates on the assumption that there is a connection between energy demand and supply. The process continues until the price of energy drops below a certain threshold level. This combination process is repeated over a five-year run, which can be extended up to 35 years. The same process is used to balance other infrastructure variables.

3. OBJECTIVE:

Objectives of the study -

a. To analyze the models to estimate the infrastructure needs based on the objectives related to investment, pricing, technology, demand, climate change and policy, and other key factors.
b. Based on the features of the model, group them into three approaches: bottom-up model, top-down model, and hybrid models, and assess each type of model, including their advantages and disadvantages.
c. Analyze the projects related to infrastructure estimation models in the Indian context.

4. METHODOLOGY

This research paper analyzes different infrastructure models utilized for estimation between 2000 and 2021. The paper follows a systematic quantitative review, as Pickering et al. (2014) suggested, and integrates existing literature on infrastructure models. This approach has been previously mentioned in works by Koc et al. (2018), Monteiro et al. (2020), and others. The existing literature estimates infrastructure demand using different sectors' top-down, bottom-up, and hybrid models. A four-step systematic quantitative review process is used: define research questions, search using keywords, select studies and databases through in-depth reading, and analyze findings for publication. The study analyzed research papers from databases, including Google Scholar, Scopus, and Web of Science, from 2000 to 2021. The papers were evaluated based on the inclusion criteria given in Table 4 to determine eligibility.

Table 4: Methodology and steps for review

1	**Definition for the area of topic**	Infrastructure Models
2	**Formulate research questions**	*Research questions.* Identification of the association between infrastructure, development, and growth. What is the difference in approach for estimating infrastructure based on micro and macroeconomics? Advantages and disadvantages of each approach.

		WWhat are the examples in the Indian context for each approach?
3	**Keywords search**	Infrastructure and Development. - Different approaches to estimate the infrastructure. - Infrastructure models. -Top-down approach in infrastructure. -Bottom-up approach in infrastructure. -Hybrid models in infrastructure.
4	**Database**	Scopus, Web of Science, and Google Scholar
5	**Criteria for inclusion**	Type of Analysis used: quantitative and qualitative. Type of Article: Research Papers published in English. Geography: Global Period: 2000–2021 Scale: District, sub-regional, country, and income-based nations. Sub-sector coverage: Power, Transport, Telecom etc.

The case studies are collected from infrastructure projects in India and categorized based on their approach.

5. ANALYSIS AND INTERPRETATION OF DATA

Most of the infrastructure exists in the form of networks, giving rise to threshold effects and returns contingent upon the network's level of completeness and the number of users. Transportation and electrical services are reliant not only on the infrastructure of roads and power plants but also on the presence of consumer durables such as automobiles, buses, trucks, refrigerators, and machines. The proximity of households or firms to markets will likely result in higher economic rewards for these services.

Infrastructure development can be undertaken for purposes other than economic expansion. Investments can be directed towards advancing social fairness, protecting the environment, enhancing public health, pursuing political objectives, or even personal enrichment.
The following are the examples of the models, grouped into three models: top-down, bottom-up, and hybrid model.

5.1 Bottom-up approach

Table 5: "Bottom-up" Approaches for Infrastructure Models

S. I	Type of Factor (Sector/technology/ objective etc)	Model	Variables used	Finding	Limitations	Sources
.	Transport energy demand	Bottom-up	mobility demand, income, fuel and technology costs, motorization rate, congestion, transport policies and lifestyle	There is a need for a mix of policy instruments, and the potential for significant reductions in transport emissions through a combination of technological innovation, behavioural change, and policy intervention.	Didn't capture all aspects of the transport system, such as the role of non-motorized transport and the potential for disruptive technological change.	Pietzcker et al. (2014)

.	Low carbon future technologies	Bottom-up	estimate energy demand and supply, including economic indicators, energy prices and costs, technological, policy measures, and environmental factors.	The models are used to estimate future energy demand, supply, and emissions, and to identify the most cost-effective and feasible pathways for transitioning to a low-carbon energy system	Models are subject to various uncertainties, such as the availability and cost of renewable energy technologies, and technological change.	Fragkos et al. (2021)
.	Bioenergy demands	Inductive, consequential Bottom-up	land use, climate-system parameters, gross domestic product growth, and technology costs.	measuring not only net carbon effects within different policy regimes but also evaluating critical infrastructural requirements	Variations in the choice of system boundaries, reference land, yields, and soil nitrous oxide emissions result in wide variations in estimates of biofuel greenhouse-gas emissions	Creutzig et al. (2012)
.	Global Bioenergy demands	Quick scan Bottom-up model	population, per capita consumption, land use, crop yields, land use, woody energy crops	The Quickscan model is a tool developed in the study to estimate global bioenergy potentials by 2050. The model evaluates three sources of biomass energy: dedicated bioenergy crops, agricultural and forestry residues and waste, and forest growth.	lack of detailed information on land use, which can affect the estimation of bioenergy potentials.	Smeets et al. (2007)
.	Energy process model	IKARUS model	energy demand, energy supply, energy prices, energy efficiency, CO2 emissions, and other environmental impacts	implementation of ambitious energy efficiency measures and the expansion of renewable energy sources could lead to significant reductions in greenhouse gas emissions and energy consumption.	all agents in the model have complete information about future developments in the energy system	Martinsen et al. (2007)
.	Energy systems	MARKAL model	The flow of yearly costs includes incurred investment costs, fixed maintenance costs, variables (the cost of materials, purchasing energy carriers, supply costs), as well as the costs of using the environment	estimate the demand for different types of energy infrastructure based on the energy demand of different sectors	long-term time horizon requires forecasts of energy demand, property rights to certificates of energy origin, and other factors that may be difficult to predict accurately.	Krzemień and Jaskólski (2015)
.	Energy modelling	TAIWAN 2050 (MARKAL) model	Electricity generation, industry, buildings, and transportation	Taiwan's carbon emission reduction targets for 2050, all sectors need to decrease energy intensity below the BAU scenario by 48% to 53%	the study does not consider important external environmental benefits for public policy decision from the social perspective	Shan Tsai and Ssu-Li Chang (2015)
.	Electricity Sector	(NEEM)Model - North American Electricity and Environment	Demand growth, available power generation, environmental technologies, and environmental regulations	Model is used to analyze the impacts of different emissions pathways on the North American electricity market, considering factors such as demand growth, available generation, environmental technologies, and both current and future environmental regulations.	Assumptions made about the behavior of market participants, the accuracy of the data, and unforeseen events or changes in policy.	Tuladhar et al. (2009)
.	Carbon-Renewal energy	Mesap-PlaNet and REMix	electricity consumption per person, industrial heat demand per GDP. sectors: Industry, transport, and residential & services, etc.	The investment costs for renewable energy technologies such as photovoltaics, concentrating solar power, wind onshore and offshore, biomass, and small hydro are projected to decrease significantly by 2050.	Infrastructure such as storage or grid extension are not considered in the model	Gils and Simon (2017)
0.	Sustainable energy	Model for Analysis of Energy Demand (MEAD)	socio-economic, technological, and demographic factors, as well as energy and electricity demand projections, and technical and policy constraints.	Future energy demand is based on medium- to long-term scenarios of socio-economic, technological, and demographic developments.	future energy demand is based on past demand-side trends and may not account for future improvements in energy efficiency and demand-side management	Kumar and Radhakrishna (2008)

5.2.2 Top-Down approach

Table 6: "Top-down" approaches for infrastructure Model

Sl	**Type of Factor (Sector/technology/ objective etc)**	**Model**	**Variables used**	**Findings**	**Limitations**	**Source**
	Needs of Infrastructure in Latin America	Fay model	Transportation, Energy, Water, and sanitation.	Estimate infrastructure needs across a cross-section of countries and a variety of sectors of Latin America.	Estimates are based on several assumptions and a high degree of uncertainty	Fay (2001)

					associated with their projections.	
	Demand estimate of infrastructure from years 2010 to 2020	Regression Model	GDP, Annual Growth, physical infrastructure.	The demand for infrastructure varies across different countries in the region, with some countries requiring more investment in energy and transport infrastructure, while others require more investment in water and sanitation infrastructure.	Methodology used in the study, may not fully capture the complexity of infrastructure demand in the region.	Bhattacharya (2010)
	Needs of Infrastructure in Asia	Econometrics Model	agricultural, industrial, urban, and population density factors.	Asia and the Pacific will need to invest around 6% of gross domestic product (GDP) in infrastructure from 2016 to 2030 to continue its recent history of generally high economic growth while ensuring new investments address the increasing urgency of infrastructure-related climate change mitigation and adaptation.	estimation of infrastructure needs is based on a set of assumptions related to economic growth, population growth, and other factors that may not hold in the future.	ADB (2017)
	Energy and Transport requirement.	Regional-CGE model	output, employment, and demand	Used for estimate future infrastructure needs	CGE models may not capture all the complexities of the real world, such as the effects of non-economic factors like social and environmental issues	Ghaith et al. (2021)
	Infrastructure and Low Carbon Future Prediction	IMACLIM-IND	GDP, Labor, Energy, Carbon emissions, trade flows, investment	The transition to a low-carbon economy in India could lead to significant economic benefits in the long run	The model's structure and assumptions may not capture all the relevant factors	Waisman et al. (2012)
	Spatial modelling	RHOMOLO model	production, consumption, investment, labor market, and migration	The model is used to simulate the impact of different policies on the economy, such as regional economic adjustment, regional spillover, and numerical general equilibrium models.	absence of financial frictions, and the lack of consideration of environmental factors	Lecca et al. (2018)
	Institutional infrastructure	EMDE model	Level financial sector, Level capital market	Estimated flows for institutional investment in infrastructure in these countries could be around USD 1 trillion building over several years	models proposed for facilitating institutional investment in infrastructure may not be suitable for all countries.	Inderst and Stewart (2014)
	Broadband infrastructure	Digital Infrastructure Costing Estimator (DICE)	Digital Infrastructure	The DICE method enables the estimation of comparative country-specific investment in digital infrastructure to achieve universal broadband connectivity.	Any global analysis will inevitably need to sacrifice country-specific detail out of necessity	Oughton, Amaglobeli & Moszoro (2023).
	Water and Health Infrastructure	Globally integrated assessment model	water access, scarcity, treatment, and efficiency with energy transformations.	Substantial investments are needed to put infrastructure, health workforce, and equipment in place and to provide essential health services.	Uncertainties related to projections, and unavailability of costing frameworks.	Parkinson et al (2019)
	Educational and health		beds in hospitals, age groups, income, and urbanization	Demand for social infrastructure, such as education and health care, is increasing in Asia.	The model does not consider the potential impact of technological advancements on infrastructure demand	Limskul & Puttanapong (2017)

5.2.3 Hybrid approach

Table 7: Different hybrid models used for infrastructure estimation in the recent past.

Sl	Factor (Sector/ objective)	Model	Variables used	Findings	Limitations	Source
	The hybrid model approach, combines top-down and bottom-up models, for investigating energy efficiency improvements.	TISMO Model	consumers, producers, government, and foreign traders, energy efficiency, technological progress	The model establishes an energy supply scenario in which at least 20% of the power supply is generated through renewable energy by 2025, consistent with the current energy policy goals of Taiwan	The model does not consider the potential impact of changes in energy prices on energy demand and economic performance.	Wu et al. (2019)
	AIM/End-use model of Indian energy systems and the IMACLIM	IMACLIM top-down & AIM/Enduse bottom-up model	National accounting, energy balance, and energy price	India's energy mix is expected to shift towards renewables, with solar and wind power	Models may not capture all the complexities of the real-world system	Gupta et al. (2020)

	model of the Indian economy			becoming increasingly competitive with fossil fuels		
	Risk assessment and cost estimation	FANP/ FBBN, also known as the Fuzzy analytical network process and /or fuzzy Bayesian belief network	Construction projects	Hybrid methods have been widely used in the construction industry for risk assessment and cost estimation under uncertainty	lack of standardization in the use of fuzzy and hybrid methods	Islam et al. (2017)
	Railway Infrastructure	Topsis	Railway Infrastructure	defect categories, the components, and the overall aggregated condition	Dynamic nature of railway infrastructure and the changes that may occur over time.	El-khateeb et al. (2021)
	Transport	Principal Component Analysis (PCA) and Fuzzy Logic	Environmental, Social, and Economic enablers	The study identifies several indicators that have a significant impact on the composite index values, such as public transport availability, road network density, and air quality.	The study focuses on four metropolitan cities in India, which may not be representative of other regions or countries.	Illahi and Shafi Mir (2021)
	Transportation	IAM IMAGE	Transportation	Rising prosperity in China, India, and Southeast Asia will quadruple light-duty vehicle sales by mid-century. Freight (road, rail, maritime, and air) and passenger aviation demand will also rise.	projections are subject to change based on new data and assumptions	Creutzig et al (2015)
	Transport	IMACLIM-R Global E3 IAM	transport	the investment needed in infrastructure increases between 2020 and 2050 in all three scenarios (low-, medium-, and high-income regions)	Growth in infrastructure for reasons other than alleviating congestion, such as upgrading roads or connecting cities to ports.	Broin & Guivarch (2017)

6. ANALYSIS AND INTERPRETATION:

6.1 Bottom-up (Microeconomic) Models

Bottom-up approaches have a significant advantage in that they provide a detailed representation of technology (Hache et al., 2019). This strength of technological details helps replicate the required sector with the help of a partial equilibrium setting (Frei et al., 2003). However, bottom-up models are not fully proven and have limited or partial economic characteristics that do not fully consider the macroeconomic reaction from other economic variables (Hache et al., 2019). This model's inability to accurately depict the economy and account for market feedback makes it unsuitable for macroeconomic analysis (Del et al., 2018).

Limitations: The traditional bottom-up model assumes straightforward capital and operational costs represent the entire social cost of technical change. This is one of its main weaknesses (Jaccard, 2005). Infrastructure assessments pose significant financial risks due to extended payback periods for irreversible expenditures. Therefore, traditional bottom-up models may lead to incorrect assessment options and policies (or policy intensities) in these cases, advising policymakers poorly (Jaccard, 2009). The bottom-up methodology's partial-equilibrium approach has limitations in assessing the macroeconomic effects of policies, specifically trade and structural implications resulting from price changes and costs throughout the economy (Tuladhar et al., 2009). Therefore, bottom-up models may suggest inappropriate policies requiring macroeconomic analysis.

6.2 Top-Down (Macroeconomic) Models

Top-down economic models involve organizing models at the regional or national level, analyzing the results, and then breaking down national outcomes like output, employment, and demand into regional outcomes. These models require fewer regional data and computational work due to their straightforward theoretical frameworks and limitations. Additionally, the modeler can apply multiplier effects based on their research goals and the unique characteristics of each region.

Limitations: The traditional top-down strategy has significant methodological flaws as well. These models calculate elasticity and efficiency improvement parameters from empirical information (Koopmans & Velde, 2001). Changing circumstances and technological advancements can invalidate derived values despite the estimated parameter intervals remaining the same. This can affect the adjustments made by enterprises and consumers, making it challenging to reflect their values accurately. Legislators are often directed toward technology-specific policies, taxes, and information initiatives instead of those that benefit the entire economy, which is a drawback of the top-down strategy (Jaccard, 2005).

6.3 HYBRID MODELS

Existing literature suggests that bottom-up models typically focus on micro or technological aspects. For example, energy-economy bottom-up models estimate energy usage and its correlation with greenhouse gas (GHG) emissions for a particular technology. These models also consider micro aspects such as market share, establishment and operation costs, and performance attributes for both the demand and supply sides. However, these models have been denounced for their limited focus on financial cost technology without considering obscure or non-monetary costs (Jaccard, 2009) and undermining the total cost, which is an aggregation of both associated with GHG abatement (Jaccard, 2005). Bottom-up models often ignore macroeconomic factors, limiting their usefulness for policies with broader economic impacts.

Top-down models typically represent macroeconomic characteristics, which can be more relevant than technological details in certain situations. These models use historical macroeconomic data to parameterize the results, implicitly capturing the most significant factors instead of the technological details. It has been observed that decision-making based solely on historical data projections may not always reflect the actual situation (Jaccard, 2009). Predictions of demand models incorporate the macroeconomic effects of policy interactions, making them helpful in modeling economy-wide policies like carbon taxes.

Studies on energy efficiency have used several models, such as top-down, bottom-up, econometric, or stochastic analysis. These models can also be applied to other sectors. The top-down model provides an overall impact analysis of the economy, while the bottom-up model provides detailed specifications such as efficiency, unit cost, and technology specifications. Hybrid models, which combine top-down and bottom-up models, are more prevalent for analyzing macro and micro factors. This text links the top-down AIM/CGE for Taiwan with the bottom-up Taiwan 2050 calculator to evaluate the impact of energy efficiency improvements in Taiwan (Wu et al., 2019). Compared to previous studies, the hybrid model provides comprehensive policy implications, not just partial evaluations.

7. CASE STUDIES RELATED TO THE ABOVE MODELS IN THE INDIAN CONTEXT.

7.1 Bottom-Up: The bottom-up approach for infrastructure estimation involves detailed, localized, and context-specific evaluation. It breaks down the analysis into smaller components like individual projects, regions, or sectors, combining them to comprehensively understand infrastructure needs. This approach emphasizes project-level analysis, stakeholder engagement, and context-specific considerations. The projects mentioned below are examples of the bottom-up approach in India (one successful and the other unsuccessful).

Table 8: Used Cases for Bottom up Models

Bottom-Up			
Name of the Project	**Sector**	**Project Description**	**Current status of the Project**
Delhi Metro, also known as DMRC.	Urban Transportation	The Delhi state government, through its organizations - the Delhi Development Authority (DDA) and the Urban Arts Commission - has proposed a transportation solution by integrating various modes of transport, linking suburban and road networks with underground mass rapid transit corridors. The Delhi Metro Rail Corporation (DMRC) was conceptualized to improve transportation in Delhi NCR and constructed in stages based on micro-economic sector decisions.	Delhi Metro is a commercial and economically viable project funded by debt and equity. As of 2022, Metro has more than 200 trains with four, six, and eight coaches, totalling around 1300 coaches. DMRC proposes to add more than 500 coaches to the route, which is up and running. DMRC will also soon develop phase 3, which may be operationalized in the coming years. During the financial year of 2015, DMRC, on average, pressed 1100 coaches in an hour (during peak hours), compared to around 800 in 2013. The average number of trips per day is about 3000.
Jaipur Metro	Transport	To address the issue of transportation stress caused by a growing population, industrialization, and development in Jaipur, the Rajasthan Government has built a Jaipur Metro - modelled after the Delhi Metro. The aim is to establish an efficient public transport network in Jaipur, reduce transport costs for all, and facilitate access to economic opportunities.	The Jaipur Metro commenced commercial operations on June 3, 2015. However, the number of passengers using the Jaipur Metro is not in line with the projected traffic study, and as per its financial records, it is currently operating at a loss. Therefore, the financial sustainability of the Jaipur Metro is uncertain. The traffic estimates were calculated inaccurately, resulting in losses for Jaipur Metro.

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7.2 Top-Down: The top-down approach to estimating infrastructure needs considers broader economic, demographic, and developmental factors to arrive at estimates. It takes a high-level perspective, analyzing overall needs and trends at a national, regional, or global level. This approach helps identify large-scale infrastructure needs and set broad targets for development. Below is an example of a top-down model in the Indian context, which estimates an investment of INR 102 lakh crores[1] by 2025.

Table 9: Used Cases for Top down Models

Top-down			
Name of the Project	**Sector**	**Project Description**	**Current status of the Project**
National Infrastructure Pipeline (India)	Physical infrastructure includes transportation, energy, telecommunication, water supply, social infrastructure, etc.	NIP includes approximately INR 100 lakh crore investment in various infrastructure sectors over five years.	IIG - India Investment Grid is a platform initiated by the Government of India, providing investors with a list of public and private sector projects and their promoters.

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The Government of India has launched a significant initiative to develop the country's infrastructure called the National Infrastructure Pipeline. It addresses the needs for infrastructure development in various industries, such as social infrastructure, urban infrastructure, digital infrastructure, transportation, electricity, and water. The NIP provides project selection, prioritization, and funding strategies, including public-private partnerships and international finance. It aims to invest INR 102 lakh crores in infrastructure development over the next five years, in line with the government's plan to grow India's economy to USD 5 trillion by 2024-2025. The NIP includes projects for economic and social infrastructure in industries such as Energy (24%), Roads (19%), Urban (16%), and Railways (13%), which make up about 70% of India's anticipated capital expenditures on infrastructure.

7.3 Hybrid approach:

The hybrid approach to infrastructure estimation combines bottom-up and top-down models. It balances detailed project-level analysis and broader macroeconomic considerations. The National Highway Development Program (NHDP) integrates both models and includes planning at project and national levels. Cost estimation and allocation are done at the individual level.

NHDP Programme (India): GoI came up with a program to develop the highways of India, namely NHDP (also known as National Highway Development Project), in the year 1998 with the help and supervision of the National Highways Authority of India (NHAI) and Ministry of Road Transport and Highways (MoRTH). The conceptualization and construction of the Golden Quadrilateral (GQ) and East West-North South (EW-NS) corridors under NHDP promoted development in the country. The NHDP projects under various phases are given below:

Table-10 : Details of Financing NHDP

[1] 1 million = 10 lakhs
10 million = 1 crore

The mentioned projects are examples of bottom-up approaches under the NHDP program in India (one was successfully implemented, and the other became a non-performing Asset)

Table-11: Used Cases for Top down Models

Name of the Project	**Sector**	**Project Description**	**Current status of the Project**
Delhi–Meerut Expressway	Road-PPP-HAM	The Delhi to Meerut Expressway was built to improve travel time and safety, as well as to enhance connectivity with parts of Uttar Pradesh and Uttarakhand. The alignment of the Delhi-Meerut Expressway (SPV) starts from Delhi (Nizamuddin Bridge) and runs parallel to the existing National Highway-24 up to Dasna in Meerut. The construction of the Expressway is divided into four sections, with a total length of 82 km. The first phase of 27.74 km will be a 14-lane road, while the rest of it will be a 6-lane expressway. The project's estimated cost is INR 4975.17 crore.	The Delhi-Meerut Expressway project was successfully implemented and achieved on the Commercial Operation Date.
Pink City Expressway	Road-PPP-BOT	National Highways Development Programme, or NHDP, was initiated in 1998 to develop road objectives aligned with international standards to facilitate easy traffic flow. Under the NHDP program of the government of India, NHAI has implemented the upgradation (from 4 lanes to 6 lanes) of the Gurugram – Kotputli – Jaipur section of NH-8 due to an increase in traffic under the BOT model.	The project faced delays in 2016 due to issues related to contracts and land acquisition. By late 2016, the project dSPV received approvals for environmental concerns, but only 96% of the physical work was completed by 2017, which was supposed to be completed by then. The non-availability of land, which was supposed to be provided by the NHAI, further increased construction costs and led to delays. In addition, the traffic estimation in the traffic study was not done properly by the NHAI, leading to a shortfall of revenue generation and NPA assets for all the lenders in the consortium.

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8. FINDINGS AND CONCLUSIONS

Estimating the necessary infrastructure is a fundamental aspect that underpins sustainable growth and the welfare of communities and nations. By conducting precise assessments of the required infrastructure, we can ensure the efficient allocation of resources, mitigating wastage and facilitating optimal utilization of cash, materials, and human resources.

Infrastructure assessment plays a crucial role in accommodating population expansion and economic activity. This ensures that our cities and regions may develop in a balanced manner, aligning with the current and future demands. The meticulous strategic planning provides vital services, including transportation, electricity, water supply, and telecommunications, with a uniform standard of excellence and dependability. Various models have evolved related to estimating infrastructure having specific factors, which may be categorized into three models.

This study shows that bottom-up models represent technology and microeconomics, while top-down models represent macroeconomics. Over time, these models have evolved and improved during the transition. Combining both creates a hybrid model with unique features and objectives.

From the literature, it can be observed that top-down models primarily represent macroeconomics, i.e., country-specific. On the other hand, bottom-up models provide specific uses of small and detailed specifications rather than general ones. For example, bottom-up models use technological specifications with or without economic ties to the micro level.

Different models use various requirements, representations, and analyses for policymakers to simulate and conduct sensitivity analysis.

Many studies have utilized different models, such as top-down, bottom-up, socio-econometric, or stochastic analysis, to analyze the importance of infrastructure. The top-down model is suitable for a consolidated analysis of infrastructure in the economy. In contrast, the bottom-up model is designed for a detailed analysis based on technological specifications, efficiencies, and micro-level factors.

It has been observed that hybrid models incorporate both top-down and bottom-up approaches for a more comprehensive analysis and to overcome any limitations of each approach. Previous studies have shown that partial evaluations with the hybrid model can provide detailed analysis and assist in making better policy decisions. However, developing countries may face unique challenges, such as meeting various goals, even though their development and growth rates may be faster. Adopting a hybrid model is recommended based on the observed drawbacks and concerns. The amalgamation of the bottom-up and top-down models is more suitable for infrastructure assessments.

9. SUGGESTIONS

Infrastructure supply drives demand, making it crucial to begin planning with predicted outcomes. Different econometric models can be used to estimate infrastructure needs, but estimations alone are unreliable. It is better to compare estimates from a combination of approaches and adopt the best-fitted model for the sector or period. Policymakers should consider a range of studies and methodologies while making investment decisions to comprehensively understand infrastructure needs and the most appropriate allocation of resources.

10. LIMITATIONS

It is important to note that the examples and case studies presented in the paper are not exhaustive and may not apply to all contexts. Further, it may also be noted that sector-specific (power, transportation, and telecom) and social infrastructure (water sanitation, education, and health) models are different.

Finally, the study does not provide a comprehensive review of the existing literature on models used for specific sectors of power, transportation, and telecom and social infrastructure (water sanitation, education, and health) as they may be different, and some readers may find the paper lacking in theoretical depth or empirical evidence.

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