**Master's Thesis**

# Shaping India's Energy Future: Energy Demand and Transport Sector Pathways

**Indiens Energiezukunft: Die Entwicklung der Energienachfrage und des Transportsektors**

Written by

Leonhard Hofbauer
ID No. XXXXXXXX

| | |
|---|---|
| **In cooperation with the** | Division of Energy Systems Analysis<br>KTH Royal Institute of Technology<br>Prof. Mark Howells |
| **Submitted to the** | Institute for Energy Economy and Application Technology<br>Technical University of Munich<br>Prof. Dr.-Ing. Ulrich Wagner |
| **Advisors** | Clara Orthofer, M.Sc.<br>Vignesh Sridharan, M.Sc.<br>Francesco Gardumi, PhD |

# Abstract

The transition to a sustainable energy system is a crucial part of India's future development. In order to shape this transition, it is vital for energy planners and policymakers to rely on profound knowledge of potential energy pathways. This work deals thoroughly with the exploration of energy demand and transport sector pathways in India.

As part of a broader research effort to build a comprehensive long-run energy system model for India, a framework for energy demand projections is developed to generate and explore future energy demand pathways. It is implemented based on different methodologies and is spanning all demand sectors of the Indian energy system. A first analysis highlights common trends and diverging characteristics of future energy demand across different societal scenarios. Based on the *Open Source Energy Modeling System* (OSeMOSYS), a transport sector model is developed as a tool to analyze future pathways of the sector. First results emphasize the carbon dependency of the Indian transport sector and the importance of a sustainable modal split on the way towards a decarbonization of the energy system.

This thesis establishes valuable groundwork for further modeling efforts as part of a sound energy planning process in India.

**Keywords: India, energy demand projections, transport sector model**

# Kurzfassung

Der Übergang zu einem nachhaltigen Energiesystem hat einen entscheidenden Anteil an der zukünftigen Entwicklung Indiens. Um diesen Übergang gestalten zu können sind Energieplaner und andere Entscheidungsträger auf ein umfassendes Verständnis von zukünftigen Energiesystementwicklungen angewiesen. Diese Arbeit beschäftigt sich tiefgehend mit der zukünftigen Entwicklung der Energienachfrage und des Transportsektors in Indien.

Als Teil eines Forschungsvorhabens zur Entwicklung eines Energiesystemmodells für Indien wird ein System für Energienachfrageprojektionen erarbeitet um Energienachfrageszenarien zu generieren und zu untersuchen. Die Berechnungen basieren auf unterschiedlichen Methodiken und umfassen alle Nachfragesektoren des indischen Energiesystems. Eine erste Analyse zeigt gemeinsame Tendenzen und unterschiedliche Ausprägungen der zukünftigen Energienachfrage in verschiedenen gesellschaftlichen Szenarien. Basierend auf dem *Open Source Energy Modeling System* (OSeMOSYS) wird ein Modell des Transportsektors entwickelt, um mögliche zukünftige Entwicklungen des Transportsektors analysieren zu können. Erste Ergebnisse unterstreichen die Kohlenstoffabhängigkeit des indischen Transportsystems und die Bedeutung einer nachhaltigen Verkehrsmittelwahl auf dem Weg zu einer Dekarbonisierung des Energiesystems.

Die Arbeit bildet eine wichtige Grundlage für die weiteren Modellierungsbestrebungen im Rahmen einer gründlichen Energiesystemplanung in Indien.

**Schlagwörter: Indien, Energienachfrageprojektionen, Transportsektormodell**

# Statement of Academic Integrity

I,

Last name: Hofbauer
First name: Leonhard
ID No.: XXXXXXXX

hereby confirm that the attached thesis,

Shaping India's Energy Future: Energy Demand and Transport Sector Pathways,

was written independently by me without the use of any sources or aids beyond those cited, and all passages and ideas taken from other sources are indicated in the text and given the corresponding citation.

I agree that public access to my work is provided and to the further use of it and its results (including programs produced and methods used) for research and instructional purposes.

The thesis has not previously been published, nor been submitted for academic credit.

Munich, November 30, 2017 ____________________

# Acknowledgements

First of all, I want to express my gratitude to Vignesh Sridharan and Francesco Gardumi for giving me the possibility to join this research project, for their guidance and for their support during the work on this thesis. Moreover, my sincere thanks go to Clara Orthofer for the co-supervision of the thesis and all the valuable advice and discussions. Furthermore, I want to thank Prof. Mark Howells and Prof. Ulrich Wagner for providing the possibility to join their research institutes and work on this thesis.

I am grateful for the collaborative work with my fellow researcher Mattia Garlaschelli and our project partners from Prayas (Energy Group), Srihari Dukkipati and Ashok Sreenivas. Moreover, I am thankful for the financial support by the European Union through the Erasmus+ program.

Last but not least, I want to extend my profound gratitude to my brother and my parents for their enduring support during my entire studies.

# Contents

# List of Figures

# List of Tables

# List of Abbreviations

## Energy carriers

| | |
|---|---|
| ATF | Aviation turbine fuel |
| CNG | Compressed natural gas |
| LNG | Liquefied natural gas |
| LPG | Liquefied petroleum gas |

## Vehicle segments

| | |
|---|---|
| 2W | Two-wheeler motorcycle |
| 3W | Three-wheeler motorcycle |
| HGV | Heavy goods vehicle |
| LGV | Light goods vehicle |

## Vehicle technologies

| | |
|---|---|
| BEV | Battery electric vehicle |
| CIEV | Compression-ignition engine vehicle |
| FCV | Fuel cell vehicle |
| GEV | Grid electric vehicle |
| GTV | Gas turbine vehicle |
| HEV | Hybrid electric vehicle |
| PHEV | Plug-in hybrid electric vehicle |
| SIEGV | Spark-ignition engine gas vehicle |
| SIEV | Spark-ignition engine vehicle |

## Others

| | |
|---|---|
| NSSO | National Sample Survey Office |
| RES | Reference energy system |
| SSP | Shared socioeconomic pathway |

# 1 Introduction

The transition to a sustainable energy system is one of the decisive challenges India is facing at the moment. From global warming to local pollution, the drastic implications of current human activities become more and more apparent and demand a transformation of the global economy. As a major source of greenhouse gases and pollutants, the energy system stands at the core of a shift towards an environmentally benign development path [1]. At the same time, the energy system in India is attributed a key role in facilitating general developmental aims [2]. Eradicating energy poverty and providing universal access to modern energy are crucial parts of a transition to a socially and environmentally sustainable energy system in India.

In order to shape this complex transition and achieve a desirable development path, it is vital for energy planners and policy-makers in India to be able to make well-informed decisions. Strategic choices are necessary in numerous areas and are often closely related to the achievement of various goals. Providing access to electricity in remote rural areas can be based on different electrification options, from grid extensions to mini-grids, while also creating the opportunity to harness local renewable energy sources for power generation [3]. In the transport sector, investment decisions in long-lived infrastructure are crucial to satisfy universal transport needs as well as to reduce greenhouse gas emissions over the next decades [4]. As part of a comprehensive energy planning process, a diverse set of tools is required to provide the necessary knowledge and insights to support fact-based decision-making towards a preferable energy system pathway in India.

One of the vital tools contributing to the energy planning process are long-run energy system models, which are of crucial interest for policy-makers to explore and analyze future pathways of the energy system and their implications. In order to contribute to the energy system planning efforts in India, a collaborative research project of the division of Energy Systems Analysis at the KTH Royal Institute of Technology in cooperation with Indian governmental and non-governmental organizations revolves around the development of a long-run energy system model for India. In a first phase, the focus is to establish a power and transport sector module based on the *Open Source Energy Modeling System* (OSeMOSYS). The model is meant to facilitate, among others, the exploration of transport sector decarbonization pathways and the optimization of power sector expansion plans over the next decades.

In the context of this research effort, this thesis contributes in two ways to the overall project. First, as a vital input to the long-run energy system model and also a crucial factor in the energy system planning process itself, this work considers the future evolution of energy demand in India. Here, the specific objective is to develop a framework and implement methodologies to facilitate scenario-based energy demand projections spanning all demand sectors of the Indian energy system. Based on the framework, a first analysis with respect to different societal pathways is conducted. Second, a transport sector model as future part of the envisaged comprehensive energy system model is developed to provide a useful tool for energy planning in India. For a first analysis, the model is used to explore decarbonization pathways of the transport sector.

The research falls in line with various other research efforts considering future energy demand and transport sector pathways in India [5–10]. Based on the commercial modeling framework MARKAL, The Energy and Resources Institute (TERI) has previously built a comprehensive energy system model to examine future Indian energy scenarios and their implications until 2036 [5]. It is driven by a framework for energy demand projections and also includes a representation of the transport sector. NITI Aayog, a Government of India think tank, has introduced a spreadsheet-based scenario generator facilitating the creation of energy demand and supply pathways for India [6]. A comprehensive MARKAL-based optimization model of the Indian energy system, including a detailed representation of transport vehicles, has been built and used to analyze, among others, co-benefits of a decarbonization of the Indian transport sector [7, 8]. As part of the overall research effort, this thesis aims to complement existing research work by contributing to the creation of powerful, yet free and open-source tools for the energy planning community.

The remaining part of this thesis is structured as follows. Chapter 2 gives an overview of the Indian energy and transport system and related future challenges, while Chapter 3 briefly introduces energy planning and underlying energy models relevant to this work. Standing at the core of the thesis, Chapters 4 and 5 explain the methodology and data basis behind the developed demand and transport sector model, respectively. Based on scenarios introduced in Chapter 6, a first set of future demand and transport sector pathways is shown and analyzed in Chapter 7. The analyses outlined in these chapters are, hereby, also capturing crucial factors for the understanding of the model limitations, the data requirement and its influence in shaping the model structures. Chapter 8 concludes the work and outlines future steps.

# 2 The Indian Energy and Transport System

In order to provide a brief background for the modeling efforts in this work, this chapter shortly discusses some major characteristics of the Indian energy and transport system. First, the primary energy consumption in India is used as a starting point to bring up main traits of the current energy system. Moreover, key aspects of the Indian transport sector with respect to its modal split and energy use are discussed before summarizing overarching challenges for India's energy system in future.

Figure 2.1 shows the composition of primary energy consumption in India in 2013. The overall consumption of 32.4 EJ constitutes 5.7 % of the global demand but given the almost 18 % share of the world's population living in India, per capita energy consumption stands only at around one third of the global average [11]. A similar situation applies to electricity, often singled out as a vital final energy carrier connected to general societal development [12]. In fiscal year 2015-16, per capita electricity consumption in India was around 1075 kWh, once more just around one third of the global average [12]. This low per capita energy consumption in India is accompanied by a large increase of the consumption of primary energy as well as electricity over the past years [11]. It draws a picture of an energy system in a phase of profound development and expansion to meet the energy needs of a rapidly emerging nation.

Considering the split of energy carriers in Figure 2.1, a large share of primary energy in India is provided by biomass. This is mainly due to the widespread use of traditional biomass for cooking. Around two thirds of the Indian population have been estimated to rely on biomass for cooking. The collection of biomass frequently results in environmental degradation and its combustion in often simple stoves can cause severe indoor pollution and, thus, health issues. At the same time, around 20 % of the population are estimated to lack access to electricity. The lack of access to modern and clean energy carriers is a vital issue for further development and alleviation of poverty in India.[6, 11]

Moreover, Figure 2.1 shows that around 73 % of India's primary energy consumption is met by fossil fuels. Here, coal with 44 % and oil with 23 % constitute the main shares whereas natural gas with 6 % of the consumption currently plays a minor role. The reliance on fossil fuels results in a high carbon intensity of the Indian energy system and consequent greenhouse gas emissions. Furthermore, the often inefficient use of fossil fuels, especially coal and oil, is a significant source of air pollution in India where air quality is a major issue in many areas [11]. For the Indian government, the high share of fossil fuels is also a concern with respect to India's energy security. Given limited domestic reserves and production capacity for natural gas and crude oil as well as a development of coal reserves falling short of domestic needs, 31 % of primary energy was imported in 2012 with an increasing share expected for the next decades.[12]

As one of the demand sectors of the Indian energy system, the transport system is partly subject to similar characteristics and consequent ramifications as outlined in the previous paragraphs. Per capita transport performance of motorized passenger and freight transport is

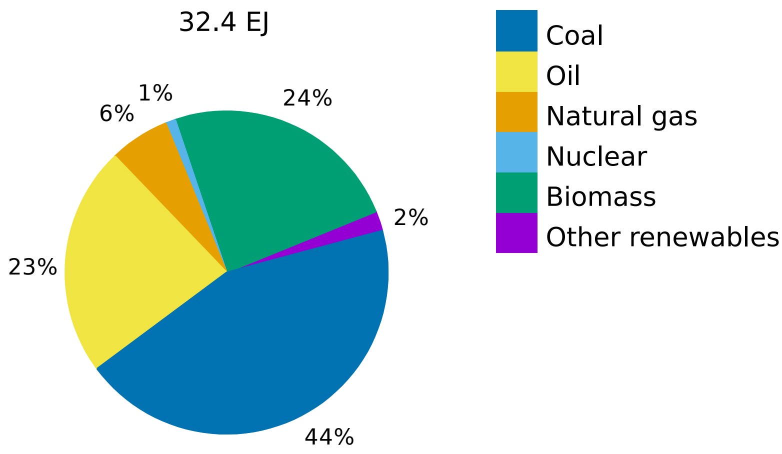


**Figure 2.1:** Composition of the primary energy consumption in India in 2013 by energy carrier. Adapted from [11].

on a low level in comparison with more advanced economies but is quickly increasing driven by economic development [7]. Both passenger and freight transport is currently dominated by road-based vehicles. In fiscal year 2011-12, an estimated 90 % of passenger mobility was provided by road transport and around 10 % by trains, whereas a negligible share was met by air-based and other transport vehicles [13]. Passenger road transport is largely characterized by bus travel as well as by a considerable utilization of 2- and 3-wheelers. The use of private cars is still limited as the ownership of cars, 29 per 1000 inhabitants in 2010, is much lower than the world average [7, 11]. Moreover, a considerable amount of short distance travel is covered by non-motorized transport modes, e.g., bicycles. Road-based transport also constitutes around 67 % of the total freight transport in 2011-12 where other major shares are provided by rail and to a lesser extent by water-, pipeline- and air-based transport [13].

Final energy consumption of the transport sector stands at 3603 PJ and constitutes only 15 % of the total consumption in 2015 [14]. It is dominated by oil products, with a high share of diesel, making up 95 % of the transport energy [11, 14] and 47 % of the overall use of oil products in India [14]. Around 91 % of the final energy consumption of the transport sector is allocated to road-based transport. The reliance on the combustion of fossil fuels to power vehicles makes the transport sector a major source for air pollution and greenhouse gas emissions in India [15, 16].

The previous paragraphs only touch upon the complex and diverse structure of the Indian energy and transport system but they expose some key features defining future overarching challenges in India. Low per capita consumption and prevalent energy poverty are demanding a rising supply of energy services in future, both as driver and consequence of future socioeconomic development. Despite potential efficiency improvements, this suggests a need for a drastic expansion of relevant parts of the energy system. At the same time, the energy system is a major contributer to local pollution and greenhouse gas emissions necessitating a transition to an environmentally benign system. Altogether, the future development of the Indian energy system will be characterized by the challenge to manage and meet future demand for energy services in an equitable and sustainable manner.[11]

# 3 Energy Planning, Demand and Energy System Models

This chapter provides a brief, non-exhaustive overview of energy planning and relevant energy demand and energy system models as useful tools in the planning process. It shortly discusses characteristics of various major modeling approaches relevant for this work.

The often long-lived and complex nature of energy systems and their interactions require strategic decisions to control their evolution in a desired manner. Especially in light of the necessary transitions ahead, this requires profound and diverse energy planning processes at different levels guiding the decision making of involved social actors at various stages. At a national level, long-term integrated energy planning incorporates a wide range of economic, environmental, social and other aspects with respect to the extraction, transmission, distribution, storage and use of energy. It can, among others, include integrated assessments, life-cycle assessments and integrated resource planning. The process relies on the application of analytical tools to support profound and comprehensive energy planning.[17]

One crucial element of energy planning is the consideration of future demand. Demand for energy services is driving the entire energy system and its satisfaction is the ultimate objective of the energy system. Therefore, the evolution of energy demand is a vital factor in defining the requirements for a future energy system. At the same time, this development is based on complex interactions of the energy system and socioeconomic, behavioral, technological, climatic and other factors [18]. Despite their limitations and remaining uncertainties, mathematical demand models can serve as useful tools to accomplish the challenging task of providing energy demand projections. A wide range of energy demand models based on a variety of methods is currently used for different projection purposes [19]. The approaches increasingly rely on a combination of different methods and cannot easily be attributed to a specific category of models [20]. Following [20], one major, non-comprehensive categorization of models distinguishes between econometric, engineering-economy or hybrid models combining both approaches.

Econometric approaches originate from economic theory. They derive a quantitative relationship between a dependent variable and one or more chosen independent economic quantities based on a statistical analysis of past data. This relationship can be established through a single equation or a complex set of equations taking into account a variety of correlations. Based on assumptions for the future evolution of the independent variables, it can then be applied to derive projections for the specified dependent variable. In contrast, the engineering-economy approach relies on a profound analysis of different end uses and relevant social, economic and technological factors to derive quantitative relationships for the projection of energy demand. Hereby, it is not constrained to replicate historic trends but can capture future structural or technological shifts. Both approaches are often combined in different ways to form an overall approach and can be used in conjunction with a set of scenarios to analyze different future pathways.[20]

To support a comprehensive energy planning process, long-term demand considerations have to be embedded in profound analyses of the entire energy system and potential future pathways. In this regard, a variety of modeling approaches with diverging characteristics with respect to their structure, capabilities, data requirement and purpose exists to aid policy-making [21]. Energy system models are commonly classified as so-called top-down or bottom-up models. Conventional top-down models tend to be concerned with the entire economy, considering the energy sector in an aggregated fashion through, e.g., production functions in the wide-spread computable general equilibrium models [22]. In contrast, bottom-up models generally strive for a detailed technological representation of the energy system but often neglect relevant interactions of, e.g., economy and energy system [22].

Particularly widely used bottom-up tools underpinning energy planning with relevant insights are long-run energy system optimization models. Based on a detailed characterization of technologies, the models minimize the cost of an energy system to meet the specified demand by optimizing the future deployment and operation of available technologies. The optimization is subject to different constraints ensuring technical conformity or, e.g., compliance with imposed environmental limits. The models often assume perfect foresight and the standpoint of a social planner while optimizing the system performance. Thus, they generate idealistic pathways which can yield valuable insights for policy-makers. Underlying modeling frameworks are for example MESSAGE [23], TIMES [24] or OSeMOSYS [25].[26]

# 4 Framework for Energy Demand Projections

The approach for scenario-based energy demand projections derived in this thesis is developed separately for various demand sectors and is based on different methods. After introducing the overall framework, its aim, and background, this chapter provides detailed explanations of the methods and underlying assumptions used for the energy demand projections of each sector. First projections, respective scenarios, and data sources are discussed in Chapters 6 and 7. The framework is implemented as spreadsheet model using the free, open-source software LibreOffice Calc. The model files can be found on the attached CD.

As stated in Chapter 1, one goal of this work is to implement a valid approach for providing energy demand projections as input for bottom-up energy system models as well as a potential direct input to the energy system planning process in India. The specific objective is to enable long-term projections considering a yearly time resolution and the country-wide, spatially aggregated demand. Moreover, the demand is to be derived separately for different demand sectors and energy carriers as outlined in the next paragraphs. Although the implementation of the framework and the different methods is partly guided by the current application to provide projections for India, it can easily be used in other contexts if respective data is available and potentially necessary methodological adjustments are undertaken.

In order to achieve this goal and provide a flexible framework for future applications, the demand projections are based on a generic two-step approach as shown in Figure 4.1. In general, the projections originate from a set of variables, so called *energy demand drivers* or simply *drivers*, which exhibit a strong correlation with the demand for energy services. These energy demand drivers can be macroeconomic, sociocultural, climatic or other parameters. Their scenario-based future evolution is exogenously defined and can be based on other models or own scenario assumptions. The evolution of the drivers is linked with the development of the energy demands through quantitative relationships. The derivation these relationships and, therefore, also the identification of relevant drivers, are based on theoretical or empirical analyses as described in Chapter 3. In a first step, relevant drivers are used to calculate the energy service demands or proxies thereof (in the following, the term energy service demand also refers to its proxies). This first step can be expressed through the simplified formula

$$ESD_s(t) = f_s(\mathbf{D}(t), \mathbf{P}), \tag{4.1}$$

where $ESD_s(t)$ is the energy service demand for a specific demand segment $s$, i.e., end use or (sub-)sector, in year $t$, $\mathbf{D}(t)$ is a vector consisting of the drivers in year $t$, $\mathbf{P}$ is a vector of constant parameters and $f_s$ is a function correlating drivers and energy service demand for segment $s$. The energy service demand itself can be the basis for crucial analyses or, if a respective demand sector model is implemented, a vital input to a bottom-up energy system model. If further analysis or modeling effort require demand projections of the final energy demand for different energy carriers, these are derived in a second step. The energy service demands are then multiplied with intensity parameters representing the usage of energy carriers to provide a specific energy service. The evolution of the parameters is defined exogenously

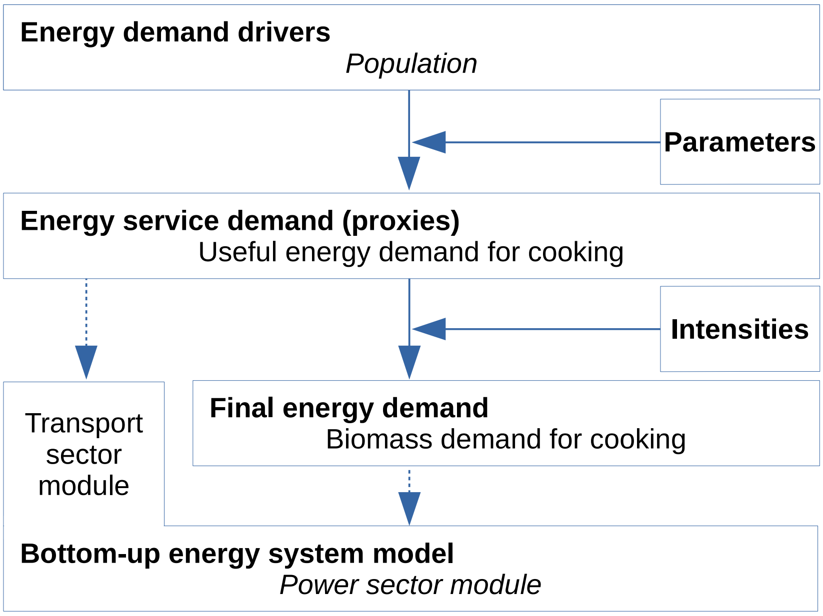


**Figure 4.1:** Sketch showing the general framework for the energy demand projections. Non-bold phrases indicate examples.

over the projection period. The following equation illustrates the concept of this second step of the energy demand projections

$$FED_{s,c}(t) = ESD_s(t) \cdot I_{s,c}(t), \tag{4.2}$$

where $FED_{s,c}(t)$ is the final energy demand of segment $s$ for energy carrier $c$ in year $t$ and $I_{s,c}(t)$ is the respective intensity parameter.

In the current work, this framework is implemented and applied based on different methods for all energy demand sectors in India. Based on [14], the residential, industry, agriculture (including forestry), service (including commerce and public services) and transport sector are considered. The sectors are defined so that the entire energy demand is captured. Although great effort is taken to consistently follow this approach throughout all demand segments, the complex and diverse concept of energy services and the limited availability of data for India make it necessary to adapt the concept to enable projections of specific demand segments.

For the residential, industry, agriculture and service sector, the demand projections include both steps in order to obtain final energy demands used as input for the power sector model. In contrast to the other sectors, the energy demand projections for the transport sector are only derived on the level of energy service demands, which are used as an input to the transport demand sector module to be introduced in Chapter 5. In order to ensure that the scenario-based projections of all sectors are based on consistent scenario assumptions, they depend on a common set of major drivers and, where appropriate, sector specific drivers and parameters. Table 4.1 shows the common and sector-specific drivers. The correlation of the drivers with the energy demand of specific end uses or (sub-)sectors and, therefore, also the rationale to include them are outlined for each of the sectors in the following sections.

**Table 4.1:** Symbols, units, and descriptions of the energy demand drivers.

| Symbol | Unit | Description |
|---|---|---|
| Major drivers | | |
| $P_t$ | - | Total population |
| $GDP$ | $\mathrm{USD}_{2010}$ | Gross domestic product |
| Sector specific drivers: Residential sector | | |
| $P_u$ | - | Fraction of the total population living in urban areas |
| $HE$ | $\mathrm{USD}_{2010}$ | Average annual per capita household expenditure |
| $HE_{R/U}$ | - | Ratio of rural to urban average per capita household expenditure |
| $HS_R$ | - | Average number of household members in rural areas |
| $HS_U$ | - | Average number of household members in urban areas |
| $CDD$ | $°\mathrm{C} \cdot \mathrm{d}$ | Average country-wide cooling degree days |
| $HDD$ | $°\mathrm{C} \cdot \mathrm{d}$ | Average country-wide heating degree days |

## 4.1 Residential Sector

The energy demand projections for the residential sector are based on a bottom-up, engineering methodology as introduced in Chapter 3. The development of a simplified bottom-up model allows for the special interest allocated to the residential sector within the overall research project while also enabling the projections to better capture structural changes expected in the sector. The bottom-up model considers the residential energy demand for five different end uses, i.e., cooking, space & water heating, lighting, space cooling, and appliances. Moreover, in order to capture the distinct nature of rural and urban areas, both are considered separately for the analysis. As outlined for the general framework in the beginning of this chapter, relevant drivers and parameters serve as basis for the calculation of energy service demands. While drivers for all sectors have already been introduced in Table 4.1, constant parameters relevant for the residential sector are summarized in Table 4.2. The energy service demands for the residential end uses are calculated as the useful energy needed to provide the specific energy service. For this analysis, the useful energy demand of lighting is specified in luminous energy, whereas for space cooling and other appliances, whose overall demand is closely related to respective ownership rates and unit energy consumptions, it is defined as the final electricity demand of the respective appliance. After introducing a general subdriver relevant for several end uses in the next paragraphs, correlations between drivers, subdriver, and useful energy demand for all residential end uses are derived in the following subsection. The overall approach is based on [9] while elements are simplified and adapted for the current purpose. It has to be noted that despite the implementation of a bottom-up methodology, the model is not based on or meant to provide a comprehensive and profound analysis of current energy demand in India but rather serves as a simple tool to derive long-term demand projections. Therefore, the correlations derived in the following paragraphs do not consider all potential linkages in a profound manner but rather rely on a limited set of drivers and parameters to reduce complexity and conform with the limited data availability.

**Table 4.2:** Symbols and descriptions of parameters used in the energy demand projections of the residential sector.

| Symbol | Unit | Description |
|---|---|---|
| $I_{SH}$ | $\frac{\mathrm{MJ}}{\mathrm{m^2 \cdot {}^\circ C \cdot d \cdot a}}$ | Useful energy intensity for space heating per floor area, heating degree day and year |
| $I_{WH}$ | MJ/d | Useful energy demand for water heating per capita and year |
| $I_C$ | MJ/d | Useful energy demand for cooking per capita per day |
| $I_{L,EL}$ | $\frac{\mathrm{lm \cdot h}}{\mathrm{m^2 \cdot a}}$ | Luminous energy intensity per floor area and year for households using electricity-based systems |
| $I_{L,KS}$ | $\frac{\mathrm{lm \cdot h}}{\mathrm{m^2 \cdot a}}$ | Luminous energy intensity per floor area and year for households using kerosene-based systems |
| $UEC_F$ | kWh/a | Annual unit energy consumption of fans for air ventilation |
| $UEC_{WM}$ | kWh/a | Annual unit energy consumption of washing machines |
| $UEC_R$ | kWh/a | Annual unit energy consumption of refrigerators |
| $UEC_T$ | kWh/a | Annual unit energy consumption of televisions |

### 4.1.1 Energy Service Demand

#### A Subdriver: The Residential Floor Space

Residential floor space is commonly used as an indicator for residential energy use [27]. It is a major influencing factor of energy demand for lighting, space heating and cooling in residential buildings [9]. Given the strong influence of the indicator on various end use applications, the residential floor space per capita $F$ is introduced as a subdriver in this analysis. In contrast to the overall drivers, it is endogenously calculated based on an econometric relationship with the main drivers of the model.

The observed average residential floor space per capita can significantly vary between different rural and urban areas and among countries and is the product of a wide range of cultural, economical and other factors [28]. On an aggregated level, per capita income is widely identified as correlating well with per capita floor space considering data for different cities and countries [28–30]. Here, residential floor space per capita $F$ is linked to another, income related factor, the per capita household expenditure $HE$. The correlation is derived based on India-specific survey data from the National Sample Survey Office (NSSO) [31] on household floor space for different expenditure classes in rural and urban areas. Following [9], the reported data points serve as basis for a regression analysis with a Gompertz curve. It can be written as

$$F_z = F_z^{sat} \cdot \exp(-m_z \cdot \exp(-n_z/1000 \cdot HE_z)), \tag{4.3}$$

where $F_z$ is the per capita residential floor space with $z \in \{rural, urban\}(= \{r, u\})$, $F_z^{sat}$ is a saturation parameter and $m_z$ and $n_z$ are fitting parameters. The saturation values $F_z^{sat}$ are assumed to be $F_r^{sat} = 40\,\mathrm{m}^2$ and $F_u^{sat} = 30\,\mathrm{m}^2$ based on reference values chosen from [28]. Figure 4.2 shows the underlying data and fitted curves for rural and urban areas. Relevant statistical indicators for this and all following fits can be found in the data files of the open-source statistical package gretl on the attached CD.

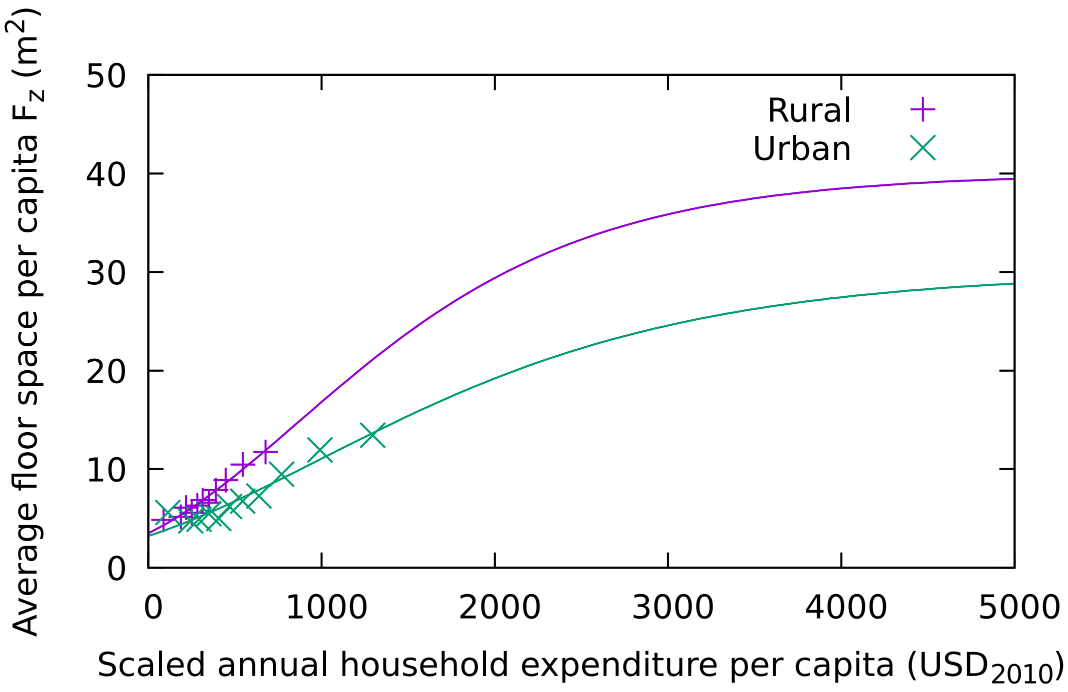


**Figure 4.2:** Per capita residential floor space as a function of scaled per capita household expenditure for rural and urban areas. Crosses indicate data points from [31], the lines show the fitted Gompertz curves with $m_r = 2.44187$, $n_r = 1.035\,23\,\mathrm{USD_{2010}}^{-1}$, $m_u = 2.23250$ and $n_u = 0.805\,272\,\mathrm{USD_{2010}}^{-1}$.

### Cooking

Whereas cooking activities constitute a small ratio of the residential energy consumption in many countries in Europe or North America, they make up a large share in other regions including India [32]. Average useful energy consumption for daily cooking activities per capita in India and other countries reported in the literature were analyzed by [9]. The data exhibit a wide dispersion but no clear correlation with income, household size or location was found. Based on [9], a constant per capita useful energy intensity for cooking $I_C = 2\,\mathrm{MJ/d}$ is chosen for the calculation of the annual cooking energy service demand

$$ESD_z^C = P_z \cdot I_C \cdot 365\,\mathrm{d/a} \tag{4.4}$$

where the population $P_z = P_t \cdot (1 - P_u)$ for $z = rural$ and $P_z = P_t \cdot P_u$ for $z = urban$.

### Space & water heating

Energy consumption for space and water heating in residential buildings in India is currently rather low [9, 29]. The useful energy demand for space heating is largely depending on climatic conditions, building characteristics and occupant behavior [33]. Following [29], the useful energy demand for space heating is estimated as

$$ESD_z^{SH} = P_z \cdot F_z \cdot HDD \cdot I_{SH} \tag{4.5}$$

where $P_z \cdot F_z$ represents the occupied floor space, the heating degree days $HDD$ are the relevant climatic parameter and $I_{SH}$ incorporates both structural building characteristics and occupant behavior. A constant space heating intensity $I_{SH} = 0.13 \, \frac{\mathrm{MJ}}{\mathrm{m^2 \cdot {}^\circ C \cdot d \cdot a}}$ is adopted from [9] for this analysis.

Average per capita energy consumption for water heating is estimated to currently be around $I_{WH} = 0.5\,\mathrm{MJ/d}$ in India. Although energy intensity is expected to increase with growing income [9], suitable data to allow for the derivation of a reasonable quantitative correlation is not readily available. For this reason and the expected limited share of water heating in the overall energy demand, energy intensity is assumed to approximately stay at current levels for this analysis. Thus, the country-wide useful energy demand for residential space and water heating is calculated as

$$ESD_z^{SWH} = ESD_z^{SH} + P_z \cdot I_{WH} \cdot 365\,\mathrm{d/a} \tag{4.6}$$

#### Lighting

The energy service demand for lighting is considered as luminous energy $ESD^L$ in lumen hours ($\mathrm{lm \cdot h/a}$). Its correlation with the drivers is based on a simplified engineering approach. Here, the luminous energy demand depends largely on the lit area, the lighting level to be achieved and the usage pattern. The average lighting level achieved strongly varies depending on the usage of electricity- ($EL$) or kerosene-based ($KS$) lighting systems, which are still used in many households in India. Therefore, separate lighting intensities for both kind of systems are introduced and energy demand is estimated considering the actual usage share of the technologies and residential floor space. Assuming simplistically the entire floor space is evenly lit, the energy service demand is calculated as

$$ESD_z^L = P_z \cdot F_z \cdot (ECS_{z,EL}^L \cdot I_{EL}^L + ECS_{z,KS}^L \cdot I_{KS}^L) \tag{4.7}$$

where $ECS_{z,EL}^L$ and $ECS_{z,KS}^L = 1 - ECS_{z,EL}^L$ are variable shares of the population using electricity- and kerosene-based lighting system, respectively. $I_{EL}^L$ and $I_{KS}^L$ are the respective lighting intensities which incorporate both usage patterns and achieved lighting level. They are calculated as

$$I_c^L = E_{v,c} \cdot u \cdot 365\,\mathrm{d/a} \tag{4.8}$$

where $E_{v,c}$ with $c \in \{EL, KS\}$ are the achieved illuminances for electricity- and kerosene-based systems and $u$ are the daily usage hours. For $E_{v,EL}$, the lower end of the range for living rooms $100\,\mathrm{lm/m^2}$ given in [34] is considered as an average for the entire residential floor space lit using electricity. For households using kerosene, an achieved illuminance of $6\,\mathrm{lm/m^2}$ is taken considering the upper end of the range given in [35], assuming an increasing prevalence of more advanced kerosene technologies. Considering an estimated average usage time of $u = 2.5\,\mathrm{h/d}$, the intensities are $I_{EL}^L = 127.8 \cdot 10^3 \, \frac{\mathrm{lm \cdot h}}{\mathrm{m^2 \cdot a}}$ and $I_{EL}^L = 7.7 \cdot 10^3 \, \frac{\mathrm{lm \cdot h}}{\mathrm{m^2 \cdot a}}$.

#### Space Cooling and Appliances

The satisfaction of the end use functions space cooling and appliances is reliant on the usage of electrical appliances and is considered together here. The energy service demand for both end uses is, hereby, closely related to the number of households owning respective appliances and their usage pattern [36]. It can be written as

$$ESD_z^{SC} = \frac{P_z}{HS_z} \cdot \sum_{a \in \mathbb{A}_{SC}} O_{a,z} \cdot \frac{UEC_a}{EF_{a,z}} \tag{4.9}$$

and

$$ESD_z^{A} = \frac{P_z}{HS_z} \cdot \sum_{a \in \mathbb{A}_{A}} O_{a,z} \cdot \frac{UEC_a}{EF_{a,z}}, \tag{4.10}$$

where $HS_z$ is the average household size in rural or urban areas, the sets $\mathbb{A}_{SC}$ and $\mathbb{A}_A$ represent appliances included for the respective end use, $O_{a,z}$ is the ownership rate of appliance $a$ in areas $z$, $UEC_a$ is the unit energy consumption of appliance $a$ and $EF_{a,z}$ the efficiency factor of appliance $a$ in areas $z$.

The demand for space cooling is met by various electric devices and there is a wide range of other appliances used in households. Following [9], washing machines, refrigerators and televisions are chosen as the three major, representative appliances to be included in the set of appliances $\mathbb{A}_A = \{WM, REF, TV\}$. For space cooling, electric fans and air conditioners are considered for $\mathbb{A}_{SC} = \{FAN, AC\}$. Air coolers are not explicitly included but are, as in the underlying data set from NSSO, considered together with air conditioners while assuming an equal consumption pattern.

The ownership rate, i.e., the share of households owning a certain appliance, is the product of many factors but is often found to correlate closely with household expenditure [9, 36]. For this work, a correlation is derived based on ownership data for different expenditure classes reported by NSSO [37] and, following [9], a Gompertz curve. It can be written as

$$O_{a,z} = O_{a,z}^{sat} \cdot \exp(-m_{a,z} \cdot \exp(-n_{a,z}/1000 \cdot HE_z)), \tag{4.11}$$

where $O_{a,z}^{sat}$ is the saturation level for appliance $a$ in rural or urban areas and $m_{a,z}$ and $n_{a,z}$ are fitting parameters.

Historic ownership saturation levels have been observed to increase over time, suggesting decreasing prices as one of the influencing factors [9]. While anticipating further increasing ownership levels, future saturation levels are set constant but at increased levels of 0.9 for televisions and 1 for all other appliances. Table 4.3 gives the values of the fitting parameters while Figure 4.3 shows data points from [37] together with the fitted Gompertz curves. It can be seen that there is partly a considerable discrepancy at higher expenditures, mainly due to assumed constant but increased saturation levels. The curves are, thus, not to be seen as best fits for data points at higher expenditure levels only to be reached in future. Instead, they incorporate an expected future development of ownership patterns, and thus different ownership rates at higher expenditure levels as suggested by historic data points.

Next to the overall number of households and the share of households owning a specific appliance, Equations (4.9) and (4.10) also incorporate the energy service demand $\frac{UEC_a}{EF_{a,z}}$ for a specific appliance if used in a household. Here, $UEC_a$ is the unit energy consumption of appliance $a$. For electric fans, washing machines, refrigerators, and televisions, constant values are chosen based on reported values in the literature and are outlined in Table 4.4. For fans, the figure implicitly includes multiple ownership by assuming an average of 1.2 fans per household owning one or more fans. The unit energy consumption of air conditioners is not based on a single device but is derived by considering the useful energy demand for space cooling with air conditioners. The correlation is based on [38], where a relationship of useful energy demand for cooling and cooling degree days for Europe based on US data is derived. Assuming a similar

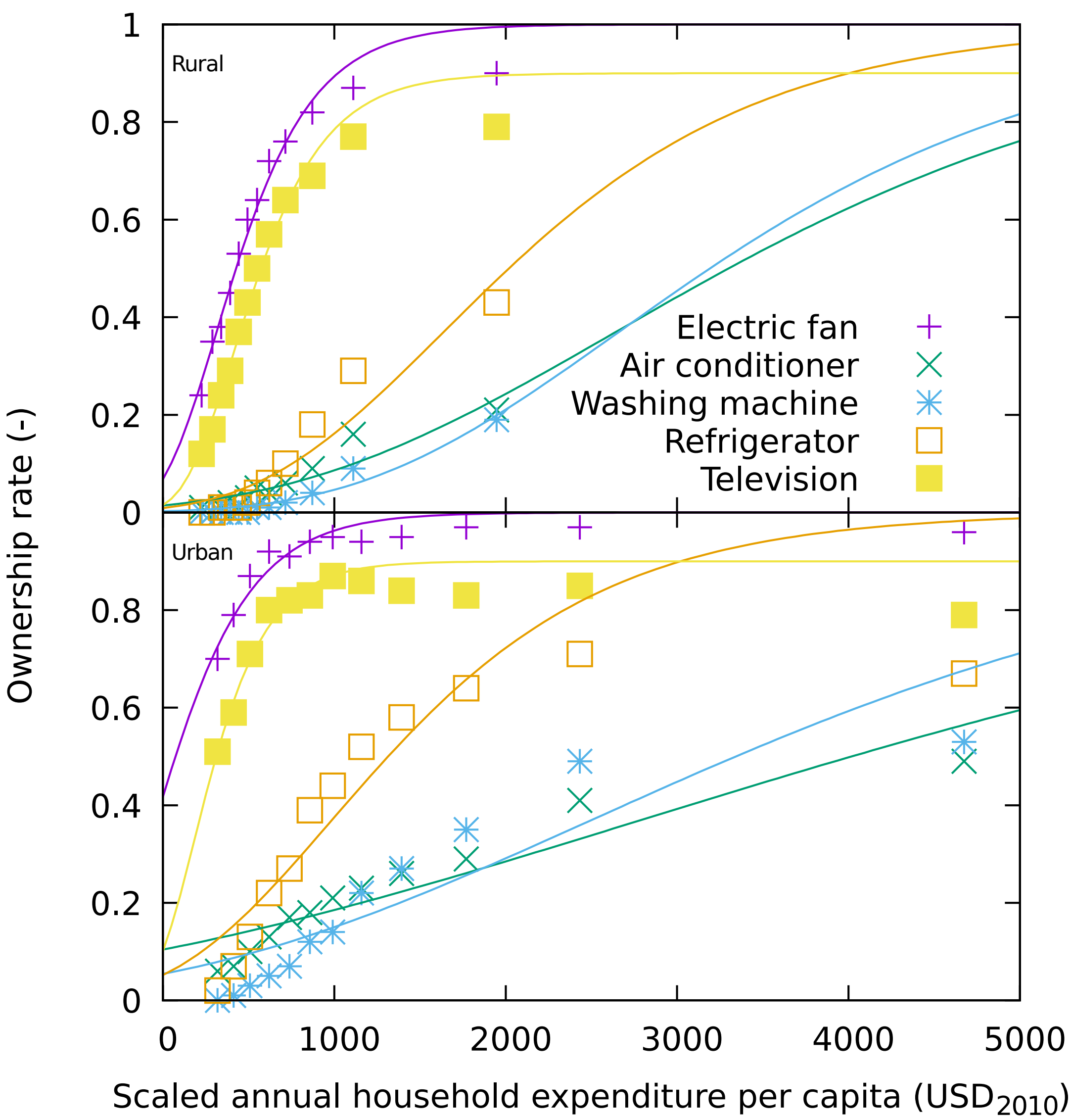


**Figure 4.3:** Ownership rates of different appliances as a function of scaled per capita household expenditure for rural on the top and urban areas on the bottom. Crosses indicate data points from [37], lines of the respective colors show the fitted Gompertz curves while fitting parameters are shown in Table 4.3.

**Table 4.3:** Values of fitting parameters for Gompertz functions linking ownership rates of appliances to scaled annual household expenditure per capita.

| **Appliance a** | $\mathbf{m_{a,r}}$ | $\mathbf{n_{a,r}}$ | $\mathbf{m_{a,u}}$ | $\mathbf{n_{a,u}}$ |
|---|---|---|---|---|
| Unit | – | ${USD_{2010}}^{-1}$ | – | ${USD_{2010}}^{-1}$ |
| *FAN* | 2.68982 | 3.17579 | 0.874941 | 3.14699 |
| *AC* | 4.24569 | 0.549131 | 2.26375 | 0.294618 |
| *WM* | 6.06149 | 0.679345 | 2.91458 | 0.429776 |
| *REF* | 4.71305 | 0.949566 | 2.9591 | 1.10451 |
| *TV* | 4.12777 | 3.40636 | 2.19411 | 4.23113 |

**Table 4.4:** Value of unit energy consumptions $UEC_a$ of appliances $a \in \mathbb{A}$. Values are adopted from [9].

| **Appliance a** | $\mathbf{UEC_a}$ |
|---|---|
| Unit | kWh/a |
| *FAN* | 174 |
| *AC* | variable, see text |
| *WM* | 190 |
| *REF* | 500 |
| *TV* | 150 |

relationship for India while taking into account the India-specific European Seasonal Energy Efficiency Ratio (ESEER) from [39], $UEC_{AC}$ is calculated as

$$UEC_{AC,z} = HS_z \cdot F_z \cdot \frac{0.051 \cdot \frac{CDD}{°\mathrm{C} \cdot \mathrm{d}} + 1.483}{ESEER} \cdot \frac{\mathrm{kWh}}{\mathrm{m}^2 \cdot \mathrm{a}}, \tag{4.12}$$

where $ESEER = 3.58$. Despite the availability of a correlation on the level of useful energy, the ESEER is used to accomplish a consistent level for the energy service demand of all appliances, i.e., useful energy demand equaling final energy demand.

Whereas the unit energy consumptions $UEC_a$ are based on a specific baseline efficiency of the devices, the variable efficiency factors $EF_{a,z}$ in Equations (4.9) and (4.10) allow for assumptions on a generic efficiency improvement of space cooling and other appliances in rural and urban areas over time. The trajectories of $EF_{a,z}$ are part of the scenario assumptions and are further considered in Chapter 6.

### 4.1.2 Final Energy Demand

Within the overall research project, the residential demand sector is currently not modeled explicitly within a bottom-up energy system model. Therefore, the energy demand is to be projected at the level of final energy in order to provide input for further analysis and a developed power system model. The demand of space cooling and other appliances derived in the previous section is already calculated at the level of final energy so no further processing is necessary. Following Equation (4.2), the final energy demand of the remaining end uses is calculated as

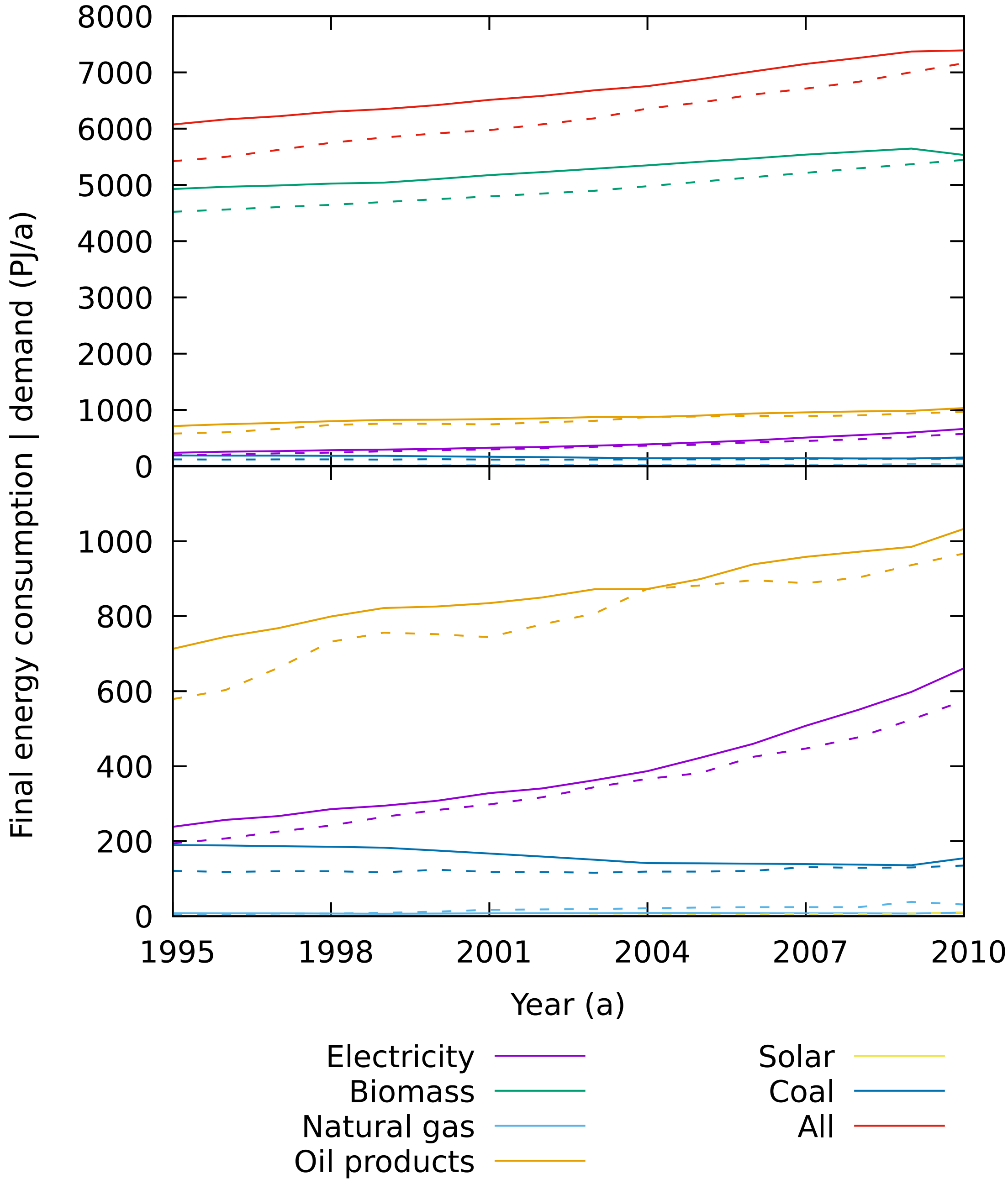


**Figure 4.4:** Results of the residential sector bottom-up demand model (solid) for the years 1995-2010 in comparison with IEA data (dashed) from [14] on two different scales. Model input data for the past years and respective sources can be found in the spreadsheet model file. Values for energy carriers have partly been summed up to match energy carrier categories reported by IEA. IEA data for biomass include biofuels and waste, data for solar include also wind and tidal energy.

$$FED_{s,c,z} = ESD_{s,z} \cdot I_{s,c,z} = ESD_{s,z} \cdot \frac{ECS_{s,c,z}}{EF_{s,c,z}} \tag{4.13}$$

where $ECS_{s,c,z}$ is the share of the rural or urban population using a specific energy carrier $c$ to fulfill the particular energy service demand of segment $s$ and $EF_{s,c,z}$ is the average efficiency of devices deployed in rural or urban areas in segment $s$ and utilizing energy carrier $c$. For space & water heating and cooking, $EF_{s,c,z}$ represents the standard energy conversion efficiency, i.e., useful energy output divided by energy input, whereas for lighting it gives the average overall luminous efficacy in lm/W. Both energy carrier shares and efficiency factors are part of the scenario assumptions and are further explained together with implemented scenarios in Chapter 6.

### 4.1.3 Model Validation

Due to the bottom-up structure of the residential demand model it is necessary to investigate its validity. This is done by testing the model performance for the years from 1995 to 2010 and comparing the results to reported data for the final energy consumption of the Indian residential sector from IEA [14]. As can be seen in Figure 4.4, the model output corresponds well with the consumption data while showing a slightly higher trajectory for most of the energy carriers. The deviation can be based on various reasons. The data reported by IEA are partly uncertain themselves, as, e.g., the use of traditional biomass is not consistently monitored. Furthermore, the model calculates the overall demand, whereas IEA data refer to final energy consumption and thus, do not include unmet demand. In the power sector, load shedding currently leads to a considerable power deficit [11], while its reported magnitude varies, e.g., from 10.6 % [40] to 24.75 % [41] in fiscal year 2009-10. Considering the 14 % lower electricity consumption reported by IEA as compared to the model results for the corresponding calender year 2009, the power deficit can be a major factor in causing the divergence of the data for electricity. However, given the simplistic nature of the model, primarily designed for demand projections, and the uncertainty and sensitivity related to its input parameters, it inherently cannot capture all aspects of the residential demand in a complete and accurate manner. Nevertheless, the comparison shows a reasonable accordance of the model with past data and, thus, allows its application for demand projections.

## 4.2 Industry, Agriculture, Service and Transport Sector

In contrast to the residential sector, the energy demand projections for the remaining sectors, i.e., industry, agriculture, service and transport sector, are based on a top-down, econometric approach as outlined in Chapter 3. This approach reduces the data requirement while facilitating consistent projections for the diverse set of sectors. Where appropriate and if necessary data are available, econometric correlations are developed separately for different subsectors or segments of the respective sector. Table 4.5 gives an overview of the implemented segments for all sectors and respective energy service demand proxies. For the industry sector, major, energy-intensive subsectors have been chosen based on [5] and data from [14]. The remaining industrial demand is attributed to an *Others* sector. The agricultural sector is split in demands for irrigation and land preparation, similar to [5] and [36]. Other agricultural demand is not separately considered but implicitly included in both other segments. Due to the diverse nature of the service sector and the unavailability of consistent data, the sector is not further broken up. The transport sector is separated into a passenger and a freight transport segment.

**Table 4.5:** Demand segments considered for the industry, agriculture, service and transport sector and their respective energy service demand proxy

| Abbreviation | Segment | Energy service demand proxy |
|---|---|---|
| Industry | | |
| IS | Iron & steel | Quantity of steel produced |
| CHE | Chemicals & petro-chemicals | Quantity of major chemicals & petro-chemicals produced |
| NFM | Non-ferrous metals | Quantity of aluminum produced |
| NMM | Non-metallic minerals | Quantity of cement produced |
| PP | Paper pulp & print | Quantity of paper & paperboard produced |
| OT | Others | Averaged quantity |
| Agriculture | | |
| IRR | Irrigation | Area irrigated by wells & tubewells |
| LP | Land preparation | Numbers of tractors in use |
| Service | | |
| SER | | $\text{GDP}_{\text{Service}}$ |
| Transport | | |
| P | Passenger | Passenger transport performance |
| F | Freight | Freight transport performance |

The respective quantity defined as energy service demand proxy for each segment is given on the right side in Table 4.5. The selection of demand proxies is strongly influenced by the availability of historic data needed for the econometric analysis. For the industry subsectors, the energy service demand proxy is defined as the demand for the major product of the subsector. Here, demand refers to the production (target) within the subsector and not to domestic demand or consumption of the product within the economy. For the *Others* sector, the energy service demand proxy is an arbitrary quantity. It is normalized with respect to the base year and linked to the average growth rate of all other industrial subsectors. For the agricultural sector, the energy service demand proxy for irrigation is the area irrigated using wells and tube wells, while the number of tractors in use is the demand proxy for land preparation. Due to aforementioned difficulties in developing a profound representation of the service sector, the sectoral gross domestic product is taken as its energy service demand proxy. The energy service demands for the transport sector segments are defined as the transport performances, i.e., distance traveled by passengers or tons of freight, respectively.

### 4.2.1 Energy Service Demand

In order to project the previously defined energy service demands, quantitative correlations between demands and scenario drivers are derived based on simple econometric models. The econometric equations are chosen in a way to fit past values as well as to exhibit a reasonable future development. For the industrial segments, a linear model linking service demand with the gross domestic product are found suitable. It can be written as

$$ESD_s = m_s + n_s \cdot GDP \tag{4.14}$$

where $m_s$ and $n_s$ are fitting parameters for segment $s$. Assuming a generic GDP growth, future values are calculated and compared to, where respective data are available, current values reported for the People's Republic of China in order to check the reasonability of the model. The irrigated agricultural area is derived as

$$ESD_s = \frac{I^{sat}}{1 + \exp\left(-(m_s + n_s \cdot GDP)\right)} \tag{4.15}$$

where $I^{sat} = 79796 \cdot 10^3$ ha is a saturation value assumed half of the total agricultural area in India as reported for fiscal year 2010-11 in [42]. The number of tractors in use is projected as

$$ESD_s = o_s + \frac{L^{sat} - o_s}{1 + \exp\left(-(m_s + n_s \cdot GDP)\right)} \tag{4.16}$$

where $o_s$ is another fitting parameter and $L^{sat} = 4760000$ is a saturation level chosen as number of tractor used in 2003 in the US, a country with a comparable agricultural area as India [43]. The correlation for the service sector is based on following equation

$$ESD_s = GDP \cdot \frac{S^{sat}}{1 + \exp\left(-(m_s + n_s \cdot GDP^{pc})\right)}. \tag{4.17}$$

Where $GDP^{pc}$ is the per capita GDP and $S^{sat} = 0.8$ is an assumed saturation value for the share of the service sector GDP. Following [7], the per capita energy service demands $ESD_s^{pc}$ of the transport sector are linked to the per capita GDP, although a different logistic model is derived

$$ESD_s^{pc} = \frac{ESD_s}{P_t} = n_s + \frac{T_s^{sat,pc} - n_s}{1 + \exp\left(-(m_s \cdot GDP^{pc})\right)}. \tag{4.18}$$

Here, $T_s^{sat,pc}$ is the per capita saturation level for transport segment $s$. The saturation levels $T_P^{sat,pc} = 20\,000$ pkm and $T_F^{sat,pc} = 8000$ pkm are adopted from [7].

As outlined in the following chapter, the bottom-up transport sector model requires energy service demands $ESD_{s_T}$ for all its different segments $s_T$, i.e., vehicle categories. The vehicle-wise projection are derived by implementing the mode share $MS_{s_T}$ of each transport segment, so that

$$ESD_{s_T} = ESD_s \cdot MS_{s_T}. \tag{4.19}$$

The evolution of the mode shares $MS_{s_T}$ are exogenously defined scenario parameters and their reasoning and use are further explained in Chapters 5 and 7.

The regression analyses are based on past data from [51] for GDP and population. The historic values for energy service demands are derived from a wide range of sources. Table 4.6 gives the sources and comments on the data, necessary processing steps and assumptions. Figure 4.5 shows the data points and respective fits for the industry, agriculture and service sector, while the analysis of the transport sector is shown separately in Figure 4.6. The resulting values of the fitting parameters can be found in the spreadsheet model on the attached CD.

**Table 4.6:** Sources of historic data and comments for the energy service demand proxies of all segments.

| **Segment** | **Sources** | **Comments** |
|---|---|---|
| Industry | | |
| IS | [44–47] | - |
| CHE | [48, 49] | - |
| NFM | [50] | - |
| NMM | [50] | - |
| PP | [43] | - |
| Agriculture | | |
| IRR | [42] | - |
| LP | [43] | - |
| Service | | |
| SER | [51],[52] | GDP from World Bank, sectoral share from Central Statistics Office. |
| Transport | | |
| P | [53, 54], [53–58], [59] | Calculated as summation of data reported for road, rail and air transport. Road: latest reported data seem unreasonable high and were not considered. Rail: Estimates for metro trains performances are added to data reported for the Indian Railways. Air: Only scheduled services are considered, data for unscheduled services are not consistently available and not least because of their limited share neglected. |
| F | [53, 54], [53–58], [59], [13, 60] | Calculated as summation of data reported for road, rail, air and estimates for water- and pipeline-based transport. Road: see above. Air: Only scheduled services are considered, data for unscheduled services are not consistently available and not least because of their limited share neglected, latest reported data seem unreasonable high and were not considered. |

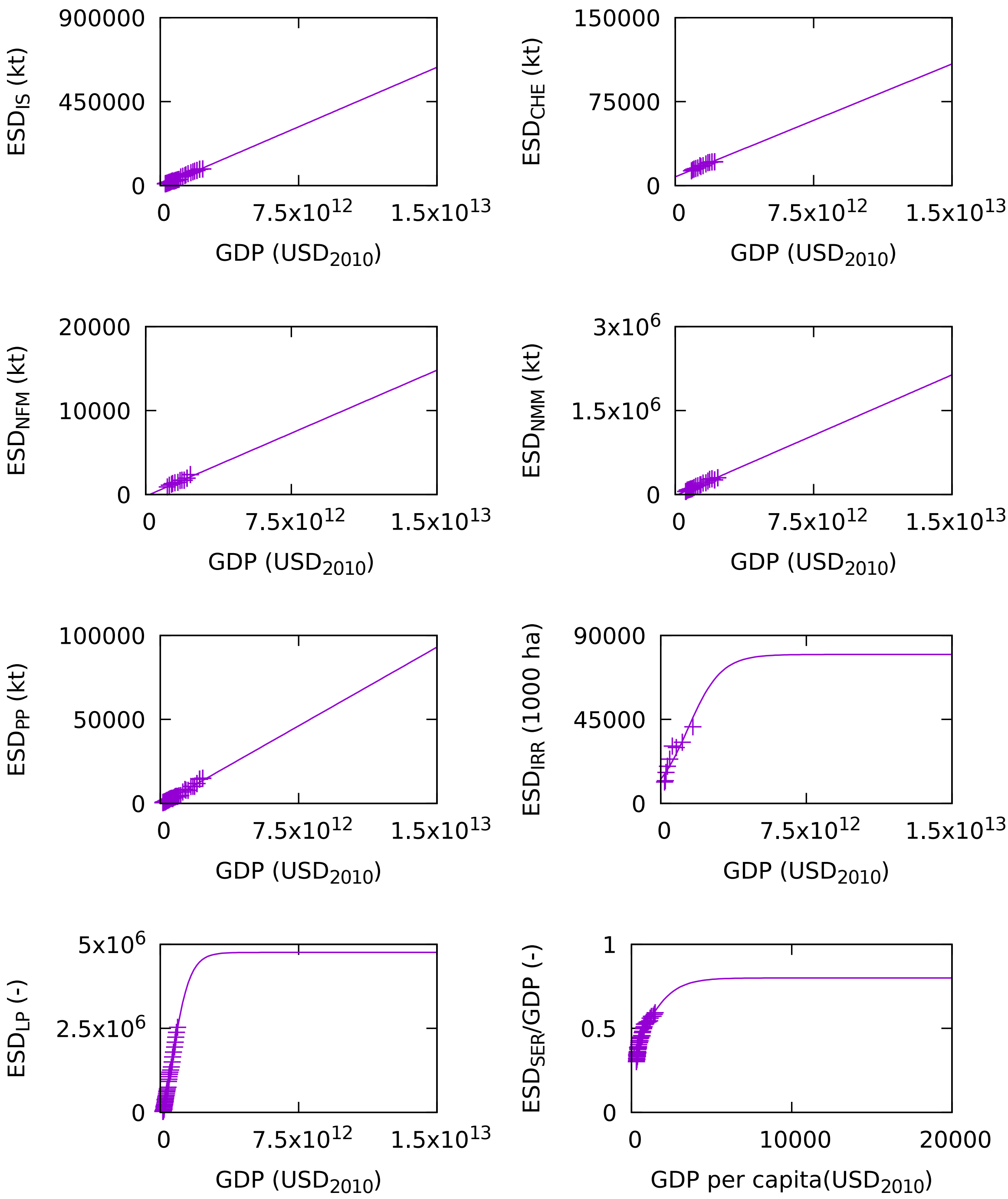


**Figure 4.5:** Historic data points and fitted regression functions for energy service demands of the industry, agriculture and service sector demand segments. The varying number and frequency of data points is due to different data sets available for each segment.

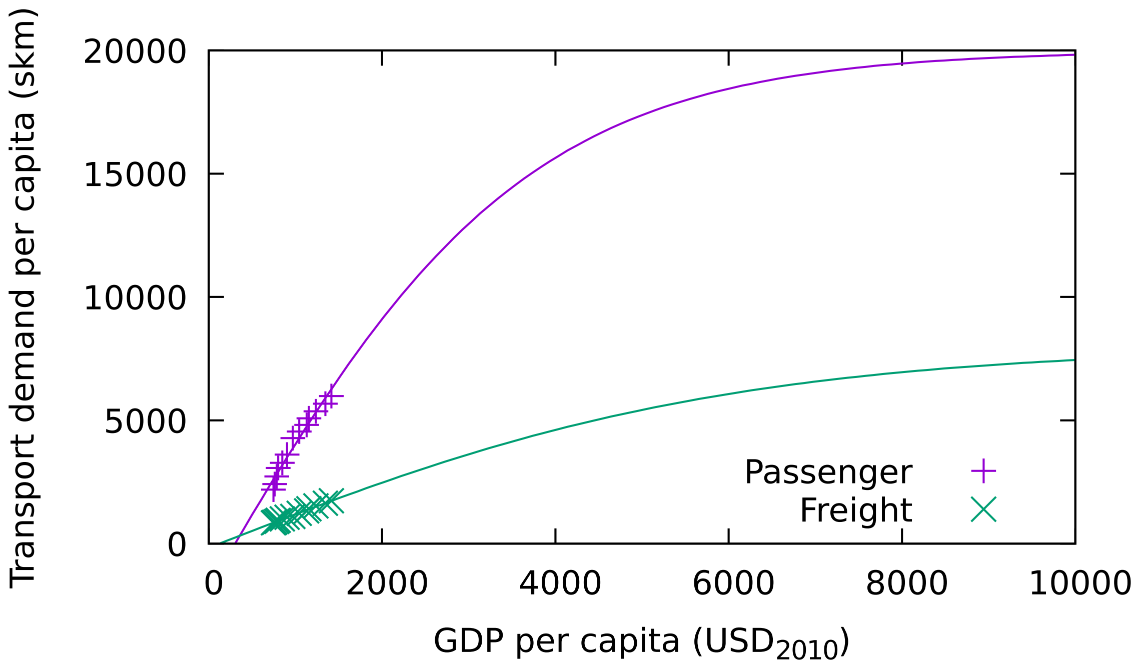


**Figure 4.6:** Historic data points and fitted regression functions for energy service demands of the transport sector. skm are *service kilometers*, i.e., pkm and tkm for passenger and freight demand, respectively.

### 4.2.2 Final Energy Demand

As with the residential demand sector, the energy demand for the industry, agriculture, and service sectors is further processed to the level of final energy in order to provide input for further analysis and the developed power system model. Based on Equation (4.2) introduced in the beginning of this chapter, the final energy demand of the sectors is calculated as

$$FED_{s,c} = ESD_s \cdot I_{s,c} \tag{4.20}$$

where $I_{s,c}$ is the energy intensity of segment $s$ considering energy carrier $c$ with respect to the energy service demand proxy of the segment. The intensities are exogenously defined scenario parameters and are further explained in Chapter 6. It has to be noted that the intensity does not necessarily equal the real energy intensity of the specific product or service chosen as demand proxy because other products or services might be provided within the same segment.

In contrast to all other sectors, the transport demand sector is modeled using OSeMOSYS and, therefore, the demand projections are only derived on the level of energy service demands, which serve as an input to the bottom-up model.

# 5 Transport Sector Model

This chapter explains the approach used to model the Indian transport sector within the framework of a long-run energy system model as introduced in Chapter 3. The transport sector model is meant to be merged with a power sector model developed within the overall research project. After briefly introducing the underlying structure of the modeling system OSeMOSYS, the representation of the Indian transport sector within this structure is discussed in detail. Moreover, the development of the necessary data basis is outlined following the description of the structure of each of the model parts. The model has been developed using the open-source interface *Model Management Infrastructure* (MoManI). Both OSeMOSYS and MoManI are freely available through `http://www.osemosys.org/`. The model files and a spreadsheet file containing all input data and underlying calculations can be found on the attached CD.

## 5.1 OSeMOSYS - A Modeling System

As introduced in Chapter 3, OSeMOSYS is an open-source, linear optimization modeling system for long-term energy system planning. It minimizes the net present cost of a system to satisfy the exogenously specified demand of energy carriers while meeting established constraints. It consists of two main materialistic elements, energy carriers and technologies. Here, energy carriers are broadly defined and also include energy services or proxies of both. The energy system is represented by technologies which consume or produce energy carriers or do both. These can be power plants generating electricity based on a fuel, e.g., biomass, pipelines transporting biofuels, or an electric car using electricity to generate an energy service. The technologies are characterized by a wide range of physical, technical, economic and other parameters. They are deployed and operated so that they meet the exogenously specified demand as well as the intermediate use of energy carriers by other technologies.[25, 61]

## 5.2 Model Implementation

Based on the previous paragraph summarizing the general structure of OSeMOSYS, the concrete implementation of energy carriers and technologies to build up the transport sector model is discussed in this section. The overall model structure can be represented by a reference energy system (RES), in which lines or arrows represent energy carriers and boxes indicated technologies. Due to its size, the comprehensive RES for the developed transport sector model is not included here but can be found on the attached CD. Figure 5.1 shows a simplified, exemplary RES depicting the vehicle technologies and fuel chains for battery electric and gasoline-powered cars and 2-wheeler motorcycles, which will serve as an example to introduce the general methodology in the following sections.

### 5.2.1 General Model Structure and Energy Service Demands

Starting on the right side of the RES in Figure 5.1, the energy service demands or rather their satisfaction is the ultimated objective of the entire energy system and also a crucial factor

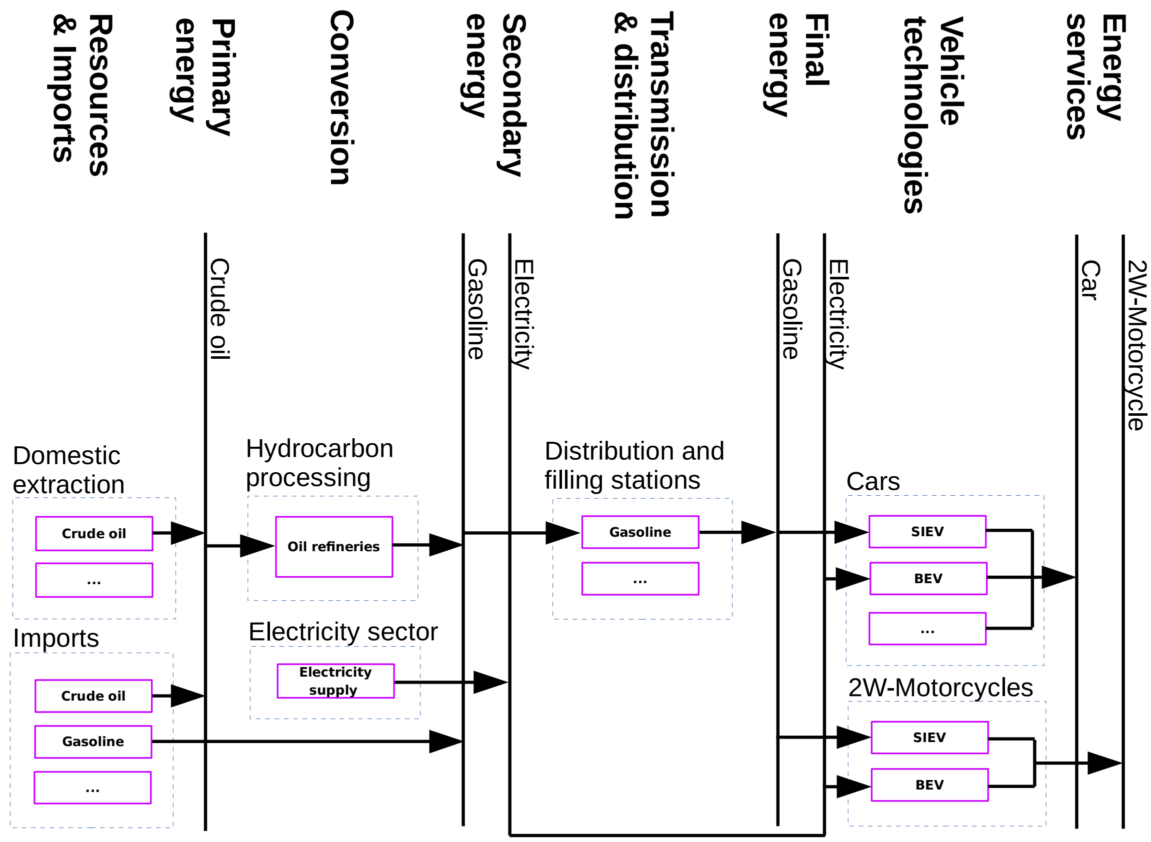


**Figure 5.1:** Simplified excerpt of the reference energy system showing exemplarily the vehicle technologies and entire energy carrier supply chain for gasoline-powered and battery electric cars and 2-wheeler motorcycles.

defining the main characteristics of the model. The energy service demands, as the entire model, are based on a temporal resolution of one year while considering India as a single, spatially aggregated model area. Here, the model considers the Indian fiscal year, spanning from the beginning of April to the end of March of the next calendar year. The demands are distinguished into passenger and freight demands, which are given in passenger-kilometers (pkm) and tonne-kilometers (tkm), respectively. The exogenously given demand is specified separately for all different motorized transport segments. Non-motorized transport is not included in the model, but its potentially changing role can be exogenously considered by defining varying demands for motorized transport. For passenger transport, the demand segments are car, 2-wheeler motorcycle (2W), 3-wheeler motorcycle (3W), bus, passenger train, and passenger airplane. Freight transport is separated in the light goods vehicle (LGV), heavy goods vehicle (HGV), freight trains, and freight airplanes segment. As necessary data is not readily available, water- and pipeline-based freight transport is currently not included in the model. Taken together, they currently constitute only around 1 % of the total final energy consumption of the Indian transport sector [14]. Furthermore, other minor segments, e.g., cable cars, are not considered.

The current specification of the transport service demands has major ramifications for the entire model and its understanding is vital for its usage and the interpretation of optimization results. The fixed, exogenously specification of the demand as required by OSeMOSYS, generally prevents any endogenous feedback between demands and other parts of the model. Moreover, the separate specification of service demands for different transport modes or segments implies that there is no competition between these segments within the model. Behavioral changes, e.g., mode shifts, are identified as vital part of a transition to a sustainable transport system and its endogenous implementation in bottom-up energy system models can be a valuable part of relevant analyses [62]. Nevertheless, the inclusion of mode competition in spatially aggregated energy system models is challenging, as the underlying consumer behavior is based on a variety of factors, e.g., travel time or comfort. As energy system models often solely consider cost, the cheapest mode would tend to be chosen to cover all demand. Although first efforts have been undertaken to include mode competition, e.g., in [63], current generation bottom-up energy system models mostly specify separate service demands in view of these major difficulties [62, 63]. Given this complexity and the focus of the current work to establish a first, extendable model version, mode competition is currently not included. Yet, acknowledging the importance of mode shifts, its influence can be included in analyses within the current framework by considering different scenarios for the exogenously specified demands.

A wide range of different vehicle types are currently in operation in India. The aforementioned vehicle segments try to establish the major vehicle categories while various specific vehicle types often existing within the segment are merged and substituted by an average or representative vehicle. For example, the passenger train segment incorporates both metro as well as long-distance intercity trains and the car segment assumes a homogeneous car market based on an average sized Indian car. Although further disaggregation of the vehicle and demand segments in, e.g., small and large cars or short and long distance travel, can provide further insights [64], this is not implemented here as necessary data are not readily available. The vehicle segments used in this work are similar to other Indian modeling efforts [5, 6].

Energy service demand data used for the different scenarios is outlined in Chapter 6 and is based on the methodology of the energy demand projections derived in Chapter 4. A discount rate of 5 % is assumed for the entire model.

### 5.2.2 Vehicle Technologies

The energy service demands of the transport sector have to be met by vehicle technologies. These technologies make use of final energy carriers in order to provide energy services. In the model, vehicles of specific technologies are built in form of their transport capacity in billion passenger- or tonne-kilometers per year derived based on their assumed performance characteristics, e.g., average annual mileage or occupancy. The vehicles are assumed to operate throughout their lifetime, i.e., the vehicle capacities in the model are always utilized fully. For each of the demand segments, there is a separate set of vehicle technologies which compete within the model based on their varying characteristics. In the RES in Figure 5.1, battery electric and gasoline-powered vehicles are shown representatively as competing technologies for both the car and 2-wheeler motorcycle segment. As the model decides solely on the basis of cost, other vehicle characteristics, e.g., comfort level or driving range, are inherently assumed to be equal among all different technology alternatives. The relevant vehicle characteristics, e.g., cost and fuel efficiency, of all alternative technologies of one segment are, therefore, derived assuming similar vehicles, which only differ in their type of powertrain. An exception to this approach is the assumed driving range for battery electric vehicles (BEVs), which is shorter than for other powertrains. For this reason, the use of BEVs is limited to a specific market share for each segment. This is further discussed in one of the following paragraphs. Moreover, the enabling transport infrastructure, e.g., roads or rail tracks, is not considered in the model, but their consistent built-up is part of potential scenario assumptions on the demand level and modal share and, therefore, the transport performance of each segment. In

**Table 5.1:** Summary of powertrain technologies and their availability in each of the vehicle segments. For trains and airplanes, the same technologies are available for both passenger and freight versions and are, thus, not separately represented in the table.

| **Vehicle technologies t** | **Availability in segment s** | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | Car | 2W | 3W | Bus | LGV | HGV | Train | Airplane |
| SIEV | √ | √ | √ | - | √ | - | - | - |
| SIE-HEV | √ | - | √ | - | √ | - | - | - |
| SIE-PHEV | √ | - | √ | - | √ | - | - | - |
| CIEV | √ | - | √ | √ | √ | √ | √ | - |
| CIE-HEV | √ | - | √ | √ | √ | √ | - | - |
| CIE-PHEV | √ | - | √ | √ | √ | √ | - | - |
| SIEGV | √ | - | √ | √ | √ | √ | - | - |
| BEV | √ | √ | √ | √ | √ | √ | - | - |
| FCV | √ | - | √ | √ | √ | √ | - | - |
| GEV | - | - | - | - | - | - | √ | - |
| GTV | - | - | - | - | - | - | - | √ |

the case of trains, the omission of infrastructure cost leads to a bias towards electric trains as additional cost for electrifying tracks are currently not considered.

There are numerous different transport fuels and powertrain technologies in various specifications, which could potentially play a vital role in a future sustainable transport system [64]. Nevertheless, for this work, a basic set of road vehicle technologies is adapted from [65] and common technologies are chosen for trains and airplanes. Table 5.1 gives an overview over the technology alternatives implemented for each of the vehicle segments. For road transport, it includes spark-ignition engine vehicles (SIEVs) and compression-ignition engine vehicles (CIEVs) running on gasoline and diesel or equivalent biofuel blends, respectively. For both engine variants, hybrid electric vehicles (HEVs) and plug-in hybrid electric vehicles (PHEVs) exist which have an electric powertrain including batteries. While HEVs have a very small sized battery, which is only charged by the vehicle engine or regenerative breaking, PHEVs have larger batteries and also use electricity as an input fuel. Moreover, the model includes, spark-ignition engine gas vehicles (SIEGVs), battery electric vehicles and fuel cell vehicles (FCVs) using compressed natural gas (CNG), electricity and hydrogen for propulsion, respectively. In addition to CIE vehicles, the rail sector entails grid-connected electric vehicles (GEVs) while the air transport sector is based on gas turbine powered vehicles (GTVs). Further explanations on the categorization and technology definitions are available in [65].

For the road transport segments, each vehicle technology is represented by five different vintages incorporating the development of vehicles available on the market starting from the vintage years 2010, 2020, 2030, 2040 and 2050. Vehicles of a specific vintage are only available to be built until the next vintage is available, e.g. from 2020 to 2029 for vehicles of the vintage year 2020. Having a longer operational life and a higher potential for retrofits, rail and air based vehicle powertrains are included as one technology with changing characteristics representing the average attributes of all respective vehicles in use.

A wide range of different parameters is necessary to properly characterize vehicles and define the respective model technologies within OSeMOSYS. The major characteristics relevant for the modeling purpose are current and future capital cost, operation & maintenance (O&M) cost, fuel efficiency and operational life. Vehicle emission characteristics for particulate matter, $NO_x$, $SO_x$, and others are currently not explicitly considered in the model. $CO_2$-eq emissions are calculated based on fuel-wise emission factors. In order to calculate the parameters with respect to the transport capacity of vehicles, the average annual mileage and the average occupancy or payload are additionally needed. Moreover, the residual capacity, i.e., the vehicle fleet in use at the beginning of the model period, of each vehicle technology is another necessary model input. Data gathered for this work are based on various publications, previous modeling efforts and bottom-up estimates. Given the number of different vehicle segments and available powertrain technologies, a vast data set is developed based on a large number of sources and various assumptions. In the following paragraphs major methods, sources and assumptions underlying the data set are explained. In view of the different approaches taken for road and rail and air transport, the road sector is considered separately. The complete data set and processing steps can be found in the model data spreadsheet on the attached CD.

#### Road transport

In order to ensure a level playing field for the different powertrain technologies within a vehicle segment, a consistent approach is necessary to derive vehicle capital cost. Here, capital cost equal the purchase price of the vehicle and are based on bottom-up estimates. The estimates are based on a profound analysis of the British vehicle market by [65], while being adapted and simplified to serve the current purpose within an Indian context. It has to be noted that a specific analysis of present and future vehicle cost in India would be desirable but is not readily available and out of scope for this work.

The road vehicle capital cost are calculated as

$$CCost_v^{s,t} = BCost_v^{s,t} \cdot \frac{1}{1 - MDMargin} \cdot PLFactor \tag{5.1}$$

where $CCost_v^{s,t}$ are the vehicle capital cost for vehicle technology $t$ of segment $s$ and vintage $v \in \{2010, 2020, ..., 2050\}$, $BCost_v^{s,t}$ are the respective basic vehicle cost and $MDMargin = 0.243$ [65] is the total margin of manufacturer and dealer, also including logistics and marketing cost. The price level factor $PLFactor = 0.29$ is based on [66] and is a measure of the general price level difference between India and the United Kingdom. Its introduction is necessary due to the current implementation of the basic vehicle cost and is further discussed in the end of this subsection.

The basic vehicle cost are calculated as the sum of the costs of major powertrain components $PTCost_v^{s,t}$, the energy storage $ESCost_v^{s,t}$ and the glider, i.e., the rest of the vehicle, $GLCost^s$ used for each of the different technology options. It can be written as

$$BCost_v^{s,t} = PTCost_v^{s,t} + ESCost_v^{s,t} + GLCost^s \tag{5.2}$$

where the powertrain cost are

$$PTCost_v^{s,t} = \sum_{p \in \mathbb{P}} EMFCost_{v,p}^s \cdot PPower_p^{s,t} + m \cdot ATCost_v^s + n \cdot EPCost_v^s. \tag{5.3}$$

**Table 5.2:** Value and source of the ICE peak power of the reference powertrain technology for the vehicles of each segment. The figures are own assumptions on representative values guided by numbers given in the respective source.

| **Segment** | **Reference powertrain** | **Peak power** | **Source** |
|---|---|---|---|
| Unit | | kW | |
| Car | SIE | 40 | [67] |
| 2W | SIE | 7.1 | [68] |
| 3W | SIE | 5.7 | [68] |
| Bus | CIE | 92 | assumed equal to HGV |
| LGV | SIE | 33 | [69] |
| HGV | CIE | 92 | [70] |

**Table 5.3:** Peak power of different components and driving ranges using a fuel tank (FT) or battery (BAT) for all powertrain technologies of the car segment.

| **Vehicle technologies** | **Peak power** | | | | | **Driving range** | |
|---|---|---|---|---|---|---|---|
| Unit | kW | | | | | km | |
| | SIE | CIE | SIEG | EM | FC | FT | BAT |
| SIEV | 40 | 0 | 0 | 0 | 0 | 500 | 0 |
| SIE-HEV | 37 | 0 | 0 | 12 | 0 | 500 | 2 |
| SIE-PHEV | 37 | 0 | 0 | 12 | 0 | 500 | 30 |
| CIEV | 0 | 40 | 0 | 0 | 0 | 500 | 0 |
| CIE-HEV | 0 | 37 | 0 | 12 | 0 | 500 | 2 |
| CIE-PHEV | 0 | 37 | 0 | 12 | 0 | 500 | 30 |
| SIEGV | 0 | 0 | 40 | 0 | 0 | 500 | 0 |
| BEV | 0 | 0 | 0 | 34 | 0 | 0 | 160 |
| FCV | 0 | 0 | 0 | 34 | 34 | 500 | 2 |

Here, $\mathbb{P} = \{SIE, SIEG, CIE, EM, FC\}$ are the scalable powertrain elements (EM: electric motor, FC: fuel cell), $EMFCost^{s}_{v,p}$ are the respective cost per peak power considering vehicle segment $s$, $PPower^{s,t}_{p}$ is the peak power of component $p$ required for vehicle technology $t$ in segment $s$, $ATCost^{s}_{v}$ are the after treatment cost for vehicles powered by an internal combustion engine (ICE) and $EPCost^{s}_{v}$ are the costs of the remaining electric powertrain elements. The parameters $m$ and $n$ are $m = 1$ and $n = 0$ for pure ICE vehicles, $m = 0$ and $n = 1$ for electric vehicles and $m = n = 1$ for hybrid vehicles.

The energy storage cost are calculated as

$$ESCost^{s,t}_{v} = \sum_{e \in \mathbb{E}} SCost^{s}_{v,e} \cdot SSize^{s,t}_{e} + l \cdot BCCost^{s}_{v}, \tag{5.4}$$

where $\mathbb{E} = \{LHC, CNG, H2, BAT_{HYB}, BAT_{BEV}\}$ are the different types of energy storage for liquid hydrocarbons ($LHC$), compressed natural gas ($CNG$), hydrogen ($H2$) and batteries for hybrids ($BAT_{HYB}$) and BEVs ($BAT_{BEV}$). $SCost^{s}_{v,e}$ are the respective cost per energy stored for segment $s$, $SSize^{s,t}_{p}$ is the storage size of type $e$ required for vehicle technology $t$ in segment $s$ and $BCCost^{s}_{v}$ are the battery charger cost with $l = 1$ for PHEVs and BEVs and otherwise $l = 0$.

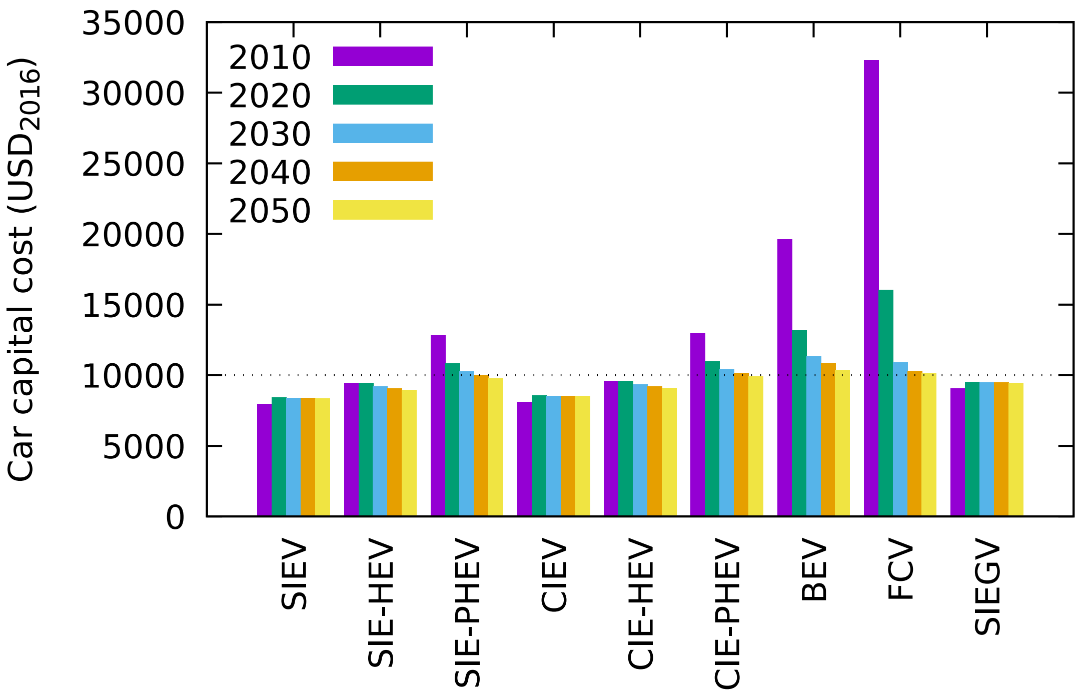


**Figure 5.2:** Capital cost of cars for all powertrain technologies and vintage years. The dotted line at 10 000 $USD_{2016}$ serves as guide to the eye.

The cost of the vehicle components and glider are mainly derived from [65] and can be found in the transport data sheet on the attached CD. In order to calculate the overall capital cost, it is necessary to further specify the aforementioned representative vehicle of each of the segments to derive peak power and storage size for each of the powertrain technologies. The ICE peak power of the reference powertrain technology, i.e., SIE or CIE vehicle, is chosen based on various India-specific sources giving information on current engine sizes. The values and sources are outlined in Table 5.2. For the remaining powertrain technologies, the peak power of powertrain components is calculated based on the peak power of the respective reference technology and the relative sizing of the components of other powertrains as given in [65]. The energy storage size is calculated assuming similar driving ranges as given in [65] while taking into account the fuel efficiencies to be discussed in following paragraphs. As the relative sizing of powertrain components and the assumed driving ranges, except for 2-wheelers, are equal for all vehicle segments, Table 5.3 representatively gives the vehicle characteristics for cars. Figure 5.2 shows the resulting capital cost. Although the bottom-up estimate is based on India-specific vehicle characteristics, the component and glider cost are rather related to the British or European market and do not account for the potentially divergent component cost and non-powertrain vehicle configuration. In the absence of consistently available India-specific cost data, a price level factor is incorporated as shown in Equation (5.1) to account for aforementioned factors. Although changes in the relative cost levels are anticipated, no clear trend in the past data for the price levels can be identified and, thus, the factor is assumed to be constant. The figure shows a slight cost increase for some conventional technologies and a sharp decrease of cost for BEVs and FCVs over time resulting in converging price levels towards 2050. A similar pattern can be seen for the other vehicle segments.

**Table 5.4:** Real-world fuel efficiency of SIE and CIE vehicles for each segment. The data are based on [71]. The SIE value for LGV and the CIE value for 3W are calculated assuming the same SIE to CIE efficiency ratio as for cars.

| **Segment**<br>Unit | **Powertrain** | **Fuel efficiency**<br>MJ/km |
|---|---|---|
| Car | SIE | 2.62 |
| | CIE | 2.85 |
| 2W | SIE | 0.66 |
| 3W | SIE | 1.70 |
| | CIE | 1.85 |
| Bus | CIE | 10.70 |
| LGV | SIE | 6.81 |
| | CIE | 7.41 |
| HGV | CIE | 13.76 |

Apart from the energy carrier cost, all O&M cost are assumed to be fixed annual cost. The fixed O&M cost $FOMCost_v^{s,t}$ are calculated as a ratio of the capital cost. They include maintenance as well as insurance cost and are derived as

$$FOMCost_v^{s,t} = CCost_v^{s,t} \cdot (MCost^t + ICost). \tag{5.5}$$

Here, $MCost^t$ and $ICost$ are the maintenance cost and insurance cost relative to the capital cost. Their values are derived based on data from [72] and own assumptions.

In order to derive fuel efficiencies consistent with the previously discussed cost, the fuel efficiencies for all vehicle technologies are also based on a bottom-up estimate following a simplified approach of [65]. Here, the fuel efficiencies of SIE and CIE vehicles of the current vintage $v = 2010$ for the different segments are based on India-specific, real-world fuel economy data from [71] and are given in Table 5.4. The fuel efficiencies of the remaining vehicle technologies $FE_{v=2010}^{s,t}$ are calculated with respected to the particular reference technology SIE or CIE for each technology, following the equation

$$FE_{2010}^{s,t} = FE_{2010}^{s,r} \cdot \frac{1 + REU^{s,t}}{1 + REU^{s,r}} \cdot (1 - EI^{s,t}). \tag{5.6}$$

Where $REU^{s,t} = \frac{[\text{on-road fuel efficiency}]^{s,t}}{[\text{reported test-cycle fuel efficiency}]^{s,t}} - 1$ is the real-world efficiency uplift for technology $t$ in segment $s$ and $EI^{s,t} = 1 - \frac{[\text{reported test-cycle fuel efficiency}]^{s,t}}{[\text{reported test-cycle fuel efficiency}]^{s,r}}$ is the respective efficiency improvement over the reference technology $r$. For PHEVs, the fuel efficiency consists of two elements, the use of hydrocarbon fuel and electricity per distance traveled. It is calculated based on the efficiency of respective HEV and BEV while assuming a share of distance traveled on each of the energy carriers given in [65]. The values for $REU$ and $EI$ are also based on [65].

The fuel efficiencies of future vehicle vintages $v \in \{2020, 2030, 2040, 2050\}$ are estimated taking into account the efficiency of the current vintage 2010 and the anticipated efficiency improvement anticipated for its components. They are calculated as

$$FE_v^{s,t} = FE_{2010}^{s,t} \cdot \frac{\sum_{c \in \mathbb{C}^t} EF_{2010}^c}{\sum_{c \in \mathbb{C}^t} EF_v^c}, \tag{5.7}$$

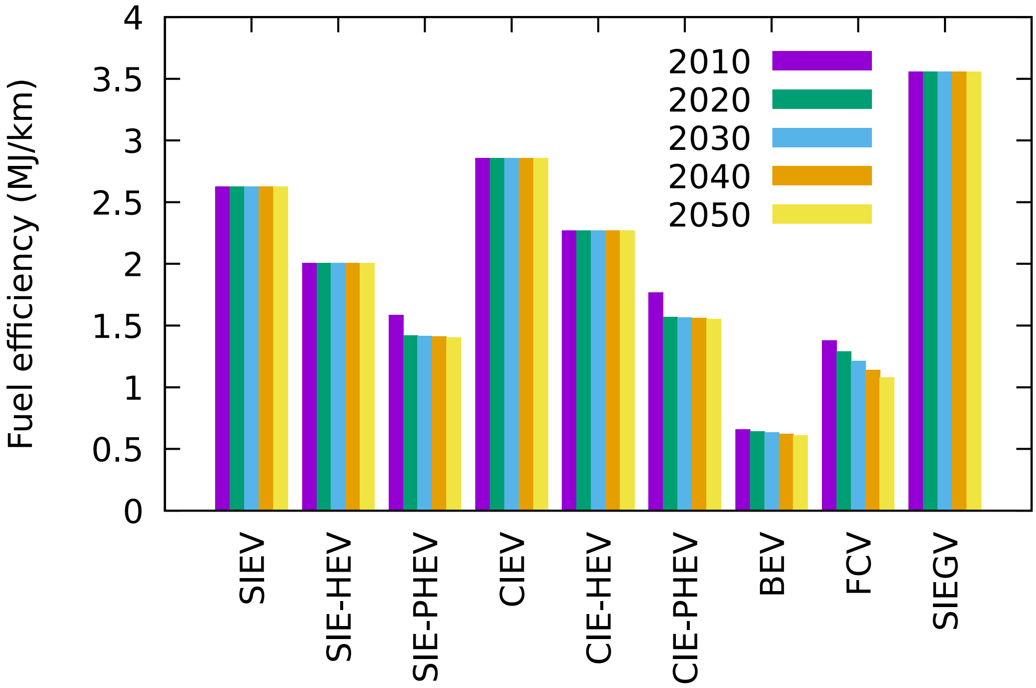


**Figure 5.3:** Fuel efficiencies of cars for all powertrain technologies and vintage years. The fuel efficiencies shown for PHEVs includes both the use of fuel as well as electricity.

where $c \in \mathbb{C}^t$ are the relevant components of technology $t$, e.g., the electric motor, the electric powertrain and batteries for BEVs, and $EF_v^c$ is the efficiency of component $c$ in vintage $v$. Future fuel efficiencies of PHEVs are again calculated based on respective HEV and BEV efficiencies. A representative overview of the calculated fuel efficiencies of cars is shown in Figure 5.3. It can be seen that the efficiency of conventional powertrains in the model stays constant, whereas the efficiency of rather new technologies is partly decreasing.

As mentioned in the beginning of the section, an upper limit is introduced for the share of the transport performance provided by BEVs. This is due to the incorporated driving ranges for BEVs, which are lower than for other vehicle technologies and are assumed to make the technology unviable to cater to parts of the demand, e.g. long-distance travel. The limits for the BEVs of all road vehicle segments are assumed based on presumptions on the share of long-distance travel and other factors. They are shown in Table 5.5.

The operational life, annual mileage, and average occupancy or payload are assumed to be equal for all vehicle technologies within one segment. Their values for all segments and respective sources are given in Table 5.6.

The residual capacities, i.e., the vehicle capacities in bpkm/a or btkm/a at the start of the modeling period, are derived based on the demand for each segment and the share of each of the vehicle technologies of the segments. Hereby, the residual capacity of a vehicle segment is assumed to be equal to the demand of the segment in the first model year. The share of the different vehicle technologies are adopted from the base year shares used in [6] and are shown in Table 5.7.

**Table 5.5:** Upper limits for the share of the transport performance provided by BEVs in each of the road vehicle segments. The values are based on own assumptions.

| **Segment** | **Upper limit** |
|---|---|
| Unit | - |
| Car | 0.25 |
| 2W | 1.00 |
| 3W | 0.80 |
| Bus | 0.25 |
| LGV | 0.80 |
| HGV | 0.25 |

**Table 5.6:** Operational life, average annual mileage and average occupancy or tonnes carried assumed for each segment. Assumption on operational life and annual mileage are based on [71], assumptions on average occupancy and payload are based on [5].

| **Segment** | **Operational life** | **Avg. annual mileage** | **Avg. occupancy or payload** |
|---|---|---|---|
| Unit | a | 1000 km | - or t |
| Car | 16 | 9.85 | 2.5 |
| 2W | 16 | 8.60 | 1.2 |
| 3W | 10 | 28.77 | 2 |
| Bus | 13 | 44.70 | 50 |
| LGV | 16 | 24.06 | 1.7 |
| HGV | 16 | 45.50 | 8 |

**Table 5.7:** Share of vehicle technologies in each road vehicle segment in the base year 2014. The values have no unit. Due to rounding, the shares may not add up to 1.

| **Vehicle technologies** | **Share in segment** | | | | | |
|---|---|---|---|---|---|---|
| | Car | 2W | 3W | Bus | LGV | HGV |
| SIEV | 0.795 | 0.998 | 0.470 | - | 0 | - |
| SIE-HEV | 0 | - | 0 | - | 0 | - |
| SIE-PHEV | 0 | - | 0 | - | 0 | - |
| CIEV | 0.184 | - | 0.422 | 0.988 | 1.000 | 1.000 |
| CIE-HEV | 0 | - | 0 | 0 | 0 | 0 |
| CIE-PHEV | 0 | - | 0 | 0 | 0 | 0 |
| SIEGV | 0.021 | - | 0.098 | 0.012 | 0 | 0 |
| BEV | 0 | 0.002 | 0.010 | 0 | 0 | 0 |
| FCV | 0 | - | 0 | 0 | 0 | 0 |

### Rail and Air Transport

In contrast to the road transport sector, no comprehensive data collection was undertaken for the rail and air sector. Instead, this work relies on data of previous modeling efforts [6] by the Indian government think tank NITI Aayog. As a profound documentation and underlying sources of the data are not available, it is acknowledged that a thorough review and own data collection efforts are necessary steps for the development of future model versions. For this first model version, data are adopted from [6] and corrected if potential data errors are identified. The data can be found in the data spreadsheet on the attached CD.

## 5.2.3 Supply, Transmission and Distribution Technologies

Apart from the vehicle technologies itself, the supply chain of final energy carriers used in the vehicles, as exemplary shown for gasoline and electricity in the RES in Figure 5.1, is a vital and decisive part of the transport and overall energy system. As no previously developed OSeMOSYS energy system model for India is available as a base for the transport sector module, the entire supply chain is modeled in this work. It has to be noted that a profound and comprehensive representation of the supply chain requires an extensive analysis, which has not been undertaken for this initial model version. Instead, a simplified representation is developed while attention was payed to consistently include costs across all energy carriers to ensure a fair competition between different vehicle technologies. All technologies are introduced based on their levelized cost and no investment or built up of capacity over years is considered. Although included through representative technologies in the model, no comprehensive analysis of biofuels and hydrogen was undertaken and both are, therefore, not considered as vital parts of future pathways analyzed in the following chapters. After introducing the structure of the supply chain, this section outlines the data assumptions.

The structure of the supply chain for all energy carriers is shown in the RES in Figure 5.4. The technologies representing the import and domestic extraction of energy carriers are depicted on the left side of the RES. Apart from electricity, all primary and secondary energy carriers are available for import while domestic extraction is considered for crude oil and natural gas. The primary energy carriers are processed in the conversion sector consisting of three distinct sectors. The hydrocarbon and biomass processing comprises four different technologies. Flexible refineries process crude oil to freely selectable splits of gasoline, diesel and aviation turbine fuel (ATF). Although future international gas pipelines projects are on the way [73], these are not considered in the model but Indian gas imports are, as currently the case, based on liquefied natural gas (LNG)[41]. Imported LNG is processed in regasification facilities while domestically extracted gas is handled in a natural gas processing unit. The production of biodiesel and ethanol can be based on a variety of raw materials and processes [74]. In India, ethanol is currently mainly derived from sugar molasses and biodiesel is, to a limited extent, produced from used cooking oil and others [75]. In the model, biofuel production is represented by a flexible biorefinery producing biodiesel and ethanol. The technology does not consider an input fuel, i.e., biomass, but instead its levelized cost include the purchase of raw material. Due to this simplified representation and the omission of the limitation of the biomass supply, biofuels are not freely available to the model vehicles but are blended in the respective liquid hydrocarbon fuel assuming a constant blend rate at current levels. A potential large-scale hydrogen production for transport systems could be based on a wide range of distributed and centralized production technologies [76, 77]. For this initial model version, only centralized alkaline water (AW) hydrolysis is introduced, whereas future, potentially cheaper and more efficient technologies are not considered. The transport sector module is meant to be combined

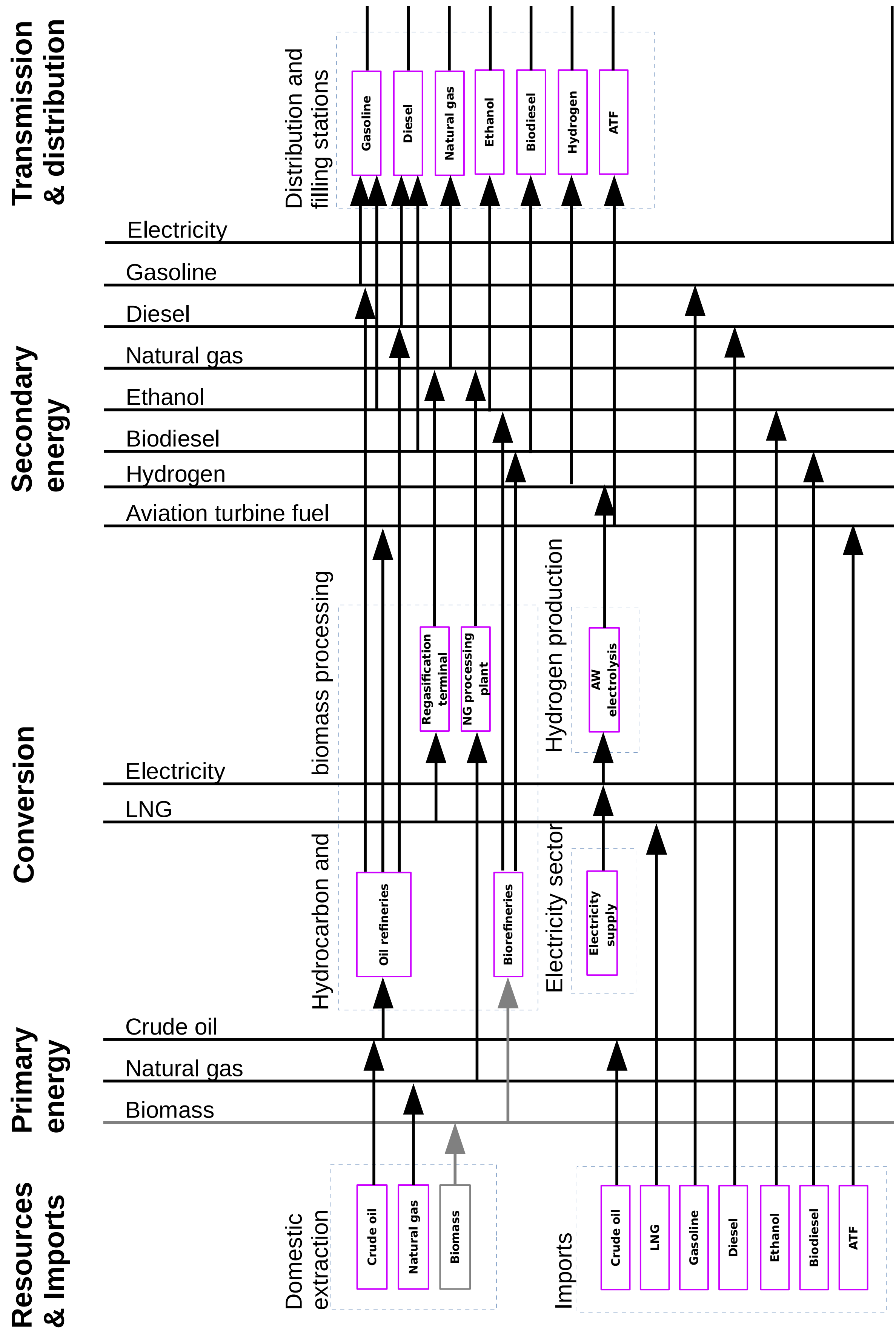


**Figure 5.4:** Excerpt of the reference energy system of the transport sector model showing the energy carrier supply chain. Grayed out technologies and energy carriers flows are shown for illustrative purposes and are not part of the model.

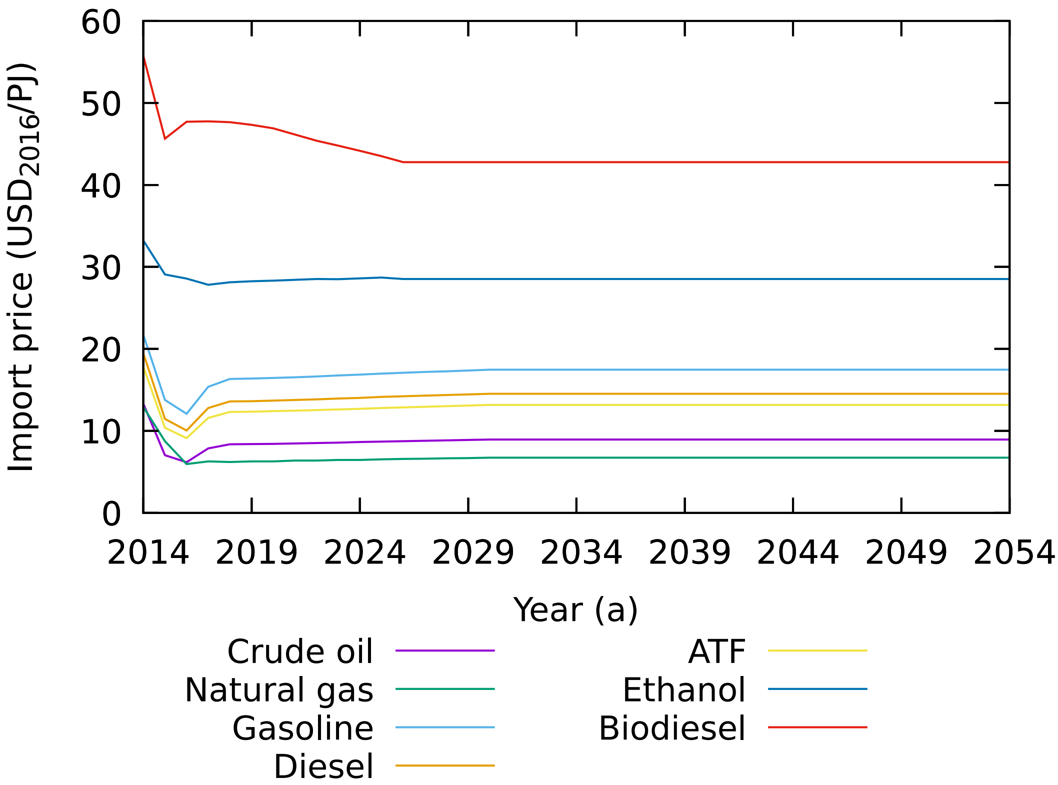


**Figure 5.5:** Evolution of the import prices for all fuels over the modeling period. Data sources are given in the text.

with a power sector module developed in parallel within the overall research project. Until a hard link between the models is established, the power generation as well as the transmission and distribution grid is represented by a single technology providing electricity to the transport system. Filling stations, transmission and distribution facilities are introduced as single technology for each diesel, gasoline, aviation turbine fuel, biodiesel, and ethanol. These technologies connect the secondary energy level to the final energy level available to vehicles. As mentioned above, transmission and distribution of electricity is included in its generation technology, while the cost of charging stations are added to the vehicle capital cost.

As discussed in the beginning of this section, most supply chain technologies are mainly characterized by their variable cost, which are set as the levelized cost of the process, and, where appropriate, the process efficiency and operational constraints. Cost and efficiency data are often site-specific and difficult to obtain. Thus, estimates are derived using indications from various sources. If not indicated otherwise, the cost and efficiencies are assumed to be constant over the modeling period.

The cost of fuel imports of the two first model years are based on actual Indian import quantities and costs reported by [75, 78], while the future growth rate is derived based on World Bank crude oil and LNG price forecasts [79] as well as OECD/FAO biofuel price forecasts [80] and is assumed constant after the forecast horizon. The large uncertainty in future world market prices is reflected in the sensitivity analysis presented in Chapter 7. Figure 5.5 shows the baseline trajectories of the Indian import prices over the modeling period. The cost of the domestic extraction of crude oil and natural gas are estimated based on upstream cost given

**Table 5.8:** Domestic extraction cost and production potential for crude oil and natural gas. The production potential increases linearly between the given values and is assumed constant after 2040. Values are derived based on [81] and [12].

| **Fuel** | **Extraction cost** | **Production potential** | | |
|---|---|---|---|---|
| Year | | 2014 | 2022 | 2040 |
| Unit | $10^6$ $USD_{2016}$/PJ | PJ/a | PJ/a | PJ/a |
| Crude oil | 3.30 | 1641.23 | 1842.19 | 2260.87 |
| Natural gas | 3.49 | 1741.81 | 1683.26 | 3439.71 |

**Table 5.9:** Emission factors for all energy carriers. Values are derived based on [51, 82, 83] and own assumptions.

| **Energy carrier** | **Emission factor** |
|---|---|
| Unit | $ktCO_2$-eq/PJ |
| Crude oil | 69.8 |
| Natural gas | 51.3 |
| Gasoline | 66.6 |
| Diesel | 69.9 |
| Aviation turbine fuel | 68.4 |
| Ethanol | 0.0 |
| Biodiesel | 0.0 |
| Electricity | 272.0 |

by [81] for, among others, the Asia-Pacific region. The annual domestic extraction of fuels is limited to the respective production potential as reported by [12] under the business-as-usual (BAU) scenario. Both costs and constraints of all technologies are summarized in Table 5.8.

The $CO_2$ emissions of the model are linked to the import and local extraction of fuels as well as to the electricity consumed. The emission factors of the fuels are based on [82], whereas the carbon intensity of consumed electricity is based on generation-level emission factor from [83] and grid losses from [51]. The emission factor for biofuels is set to zero for this analysis. Consequent emission factors are given in Table 5.9.

The cost of refineries is estimated based on investment cost for an India-based project and other parameters from [84] and [85]. The variable cost as well as the efficiency is assumed to be equal for all combinations of output fuels. It is set to the average efficiency reported for the US in [84]. For natural gas processing plants, costs are estimated based on data reported in [86], while the cost for regasification terminals is approximated by regasification charges from [87]. The efficiency of both technologies is assumed to be 1. The biorefinery technology does not have an input fuel and its cost include expenses for raw material. It is approximated by respective market prices reported in [75] and [88]. Cost and efficiency data for centralized alkaline water hydrolysis plants are based on values reported in [77], where a linear interpolation is applied between current and 2025 data. The levelized cost of electricity is estimated based on [89] and [51]. The data input for the conversion sector of the model is summarized in Table 5.10.

The representation of energy carrier distribution in spatially aggregated energy system models can be difficult as, e.g., spatial characteristics can be decisive for the cost of pipelines [90].

**Table 5.10:** Cost and efficiencies of the conversion sector facilities. Underlying sources are outlined in the text.

| **Facility**<br>Unit | **Levelized cost**<br>$10^6$ $USD_{2016}/PJ$ | **Efficiency**<br>- |
|---|---|---|
| Oil refinery | 1.00 | 0.91 |
| NG processing plant | 0.48 | 1.00 |
| LNG regasification plant | 0.62 | 1.00 |
| Biorefinery (Ethanol\|Biodiesel) | 28.51\|16.68 | - |
| Alkaline water electrolyser (2014\|2025) | 4.17\|1.80 | 0.74\|0.89 |
| Electricity sector | 40.35 | - |

**Table 5.11:** Cost of the energy carrier distribution facilities. Hydrogen distribution cost decrease between 2014 and 2040. Underlying sources are outlined in the text.

| **Energy carrier**<br>Unit | **Levelized distribution cost**<br>$10^6$ $USD_{2016}/PJ$ |
|---|---|
| Gasoline | 1.80 |
| Diesel | 1.63 |
| Aviation turbine fuel | 1.63 |
| CNG | 9.51 |
| Ethanol | 2.44 |
| Biodiesel | 1.79 |
| Hydrogen (2014\|2040) | 79.64\|20.55 |
| Electricity | - |

For this thesis, the distribution costs are mainly derived from values for Germany assembled by [91]. Table 5.11 gives the cost associated with the distribution of each fuel. The efficiency is assumed to be 1 for all technologies. While no biodiesel is used in the model, gasoline is assumed to be blended with ethanol. Hereby, ethanol is making up 2 % of the energy content of the blended fuel, similar to the current average blend rate reported in [75]. As mentioned above, electricity transmission and distribution cost are included in the electricity supply technology whereas charging stations are added to the vehicle capital cost. Based on [90] and aforementioned price level factor, additional cost for charging stations per vehicle are calculated as 761 $USD_{2016}$ for PHEVs and 1361 $USD_{2016}$ for BEVs.

# 6 Scenarios - Defining Future Pathways

The methodology for deriving energy demand projections and the transport sector model introduced in the previous chapters are to be used to explore and investigate future pathways of the Indian transport and energy system from 2014 to 2054, i.e., fiscal year 2014-15 to 2054-55. For this purpose, first scenarios representing the baseline of various potential future pathways are presented and discussed in the following sections, whereas results are discussed in Chapter 7.

## 6.1 Energy Demand Scenarios

In this work, different possible futures of the energy demand in India are explored with respect to distinct evolutions of society. The scenarios are based on the shared socioeconomic pathways (SSPs) developed by the climate change research community as part of a joint effort to provide consistent scenarios for analyses of, among others, climate adaptation and mitigation challenges and strategies [92]. The five basic SSPs represent distinct pathways of society and ecosystem while assuming no enactment of climate-related policies [93]. Table 6.1 gives summaries of the qualitative narratives of the SSPs as described in [94]. In order to develop energy demand projections for the different pathways it is necessary to quantitatively describe relevant key characteristics, i.e., energy demand drivers and parameters as discussed in Chapter 4.

In line with the qualitative descriptions of the SSPs, quantitative characterizations of key scenario drivers for each of the SSPs have been developed by the research community [95–99] and are available through the SSP database (`https://tntcat.iiasa.ac.at/SspDb`). For this thesis, population projections of the model *IIASA-WiC POP* [95], urbanization trends of *NCAR* [96] and GDP growth of *IIASA GDP* [97] are retrieved from the SSP database. In order to establish common values for the base year 2014 of this analysis, these are adopted from [51] while the evolution is based on decade-wise growth rates of the respective projections. Figure 6.1 shows the evolution of these key drivers over the modeling period of this work. Apart from these major influencing factors of the future energy demand, the evolution of remaining drivers of the residential sector, as outlined in Table 4.1 in Chapter 4, are derived as follows. For the average annual per capita household expenditure *HE* the base year value is taken from [51] while its evolution is assumed to exhibit the same growth rate as the per capita GDP. The ratio of rural to urban average per capita household expenditure is derived from past values given in [37] and own assumptions for the future evolution. In line with the rising equality in SSP1, a linear increase from 0.53 in 2014 to 0.8 in 2054 is assumed for this scenario, whereas an increase to 0.6 is assumed for SSP2 and SSP5. For the remaining SSPs, a constant ratio is anticipated. [100] identifies a declining average household size as demographic trend throughout different world regions. Here, the evolution of the average household size in rural and urban areas is based on past data from [101] and a similar trajectory as derived by [100] for India. This implies a decrease from base year values of 4.8 and 4.5 to 3.5 and 3.4 for rural and urban households, respectively. It is assumed to be equal across all scenarios. Despite the varying challenge to climate change adaptation implicated in the SSPs, heating and cooling degree days as climatic variables are assumed to exhibit a similar behavior across all SSPs over the

**Table 6.1:** Qualitative narratives of the shared socioeconomic pathways. Adopted from [94].

| SSP1: “Sustainability - Taking the Green Road” |
|---|
| “The world shifts gradually, but pervasively, toward a more sustainable path, emphasizing more inclusive development that respects perceived environmental boundaries. Management of the global commons slowly improves, educational and health investments accelerate the demographic transition, and the emphasis on economic growth shifts toward a broader emphasis on human well-being. Driven by an increasing commitment to achieving development goals, inequality is reduced both across and within countries. Consumption is oriented toward low material growth and lower resource and energy intensity.” |
| SSP2: “Middle of the Road” |
| “The world follows a path in which social, economic, and technological trends do not shift markedly from historical patterns. Development and income growth proceeds unevenly, with some countries making relatively good progress while others fall short of expectations. Global and national institutions work toward but make slow progress in achieving sustainable development goals. Environmental systems experience degradation, although there are some improvements and overall the intensity of resource and energy use declines. Global population growth is moderate and levels off in the second half of the century. Income inequality persists or improves only slowly and challenges to reducing vulnerability to societal and environmental changes remain.” |
| SSP3: “Regional Rivalry - A Rocky Road” |
| “A resurgent nationalism, concerns about competitiveness and security, and regional conflicts push countries to increasingly focus on domestic or, at most, regional issues. Policies shift over time to become increasingly oriented toward national and regional security issues. Countries focus on achieving energy and food security goals within their own regions at the expense of broader-based development. Investments in education and technological development decline. Economic development is slow, consumption is material-intensive, and inequalities persist or worsen over time. Population growth is low in industrialized and high in developing countries. A low international priority for addressing environmental concerns leads to strong environmental degradation in some regions.” |
| SSP4: “Inequality - A Road Divided” |
| “Highly unequal investments in human capital, combined with increasing disparities in economic opportunity and political power, lead to increasing inequalities and stratification both across and within countries. Over time, a gap widens between an internationally-connected society that contributes to knowledge- and capital-intensive sectors of the global economy, and a fragmented collection of lower-income, poorly educated societies that work in a labor intensive, low-tech economy. Social cohesion degrades and conflict and unrest become increasingly common. Technology development is high in the high-tech economy and sectors. The globally connected energy sector diversifies, with investments in both carbon-intensive fuels like coal and unconventional oil, but also low-carbon energy sources. Environmental policies focus on local issues around middle and high income areas.” |
| SSP5: “Fossil-fueled Development - Taking the Highway” |
| “This world places increasing faith in competitive markets, innovation and participatory societies to produce rapid technological progress and development of human capital as the path to sustainable development. Global markets are increasingly integrated. There are also strong investments in health, education, and institutions to enhance human and social capital. At the same time, the push for economic and social development is coupled with the exploitation of abundant fossil fuel resources and the adoption of resource and energy intensive lifestyles around the world. All these factors lead to rapid growth of the global economy, while global population peaks and declines in the 21st century. Local environmental problems like air pollution are successfully managed. There is faith in the ability to effectively manage social and ecological systems, including by geo-engineering if necessary.” |

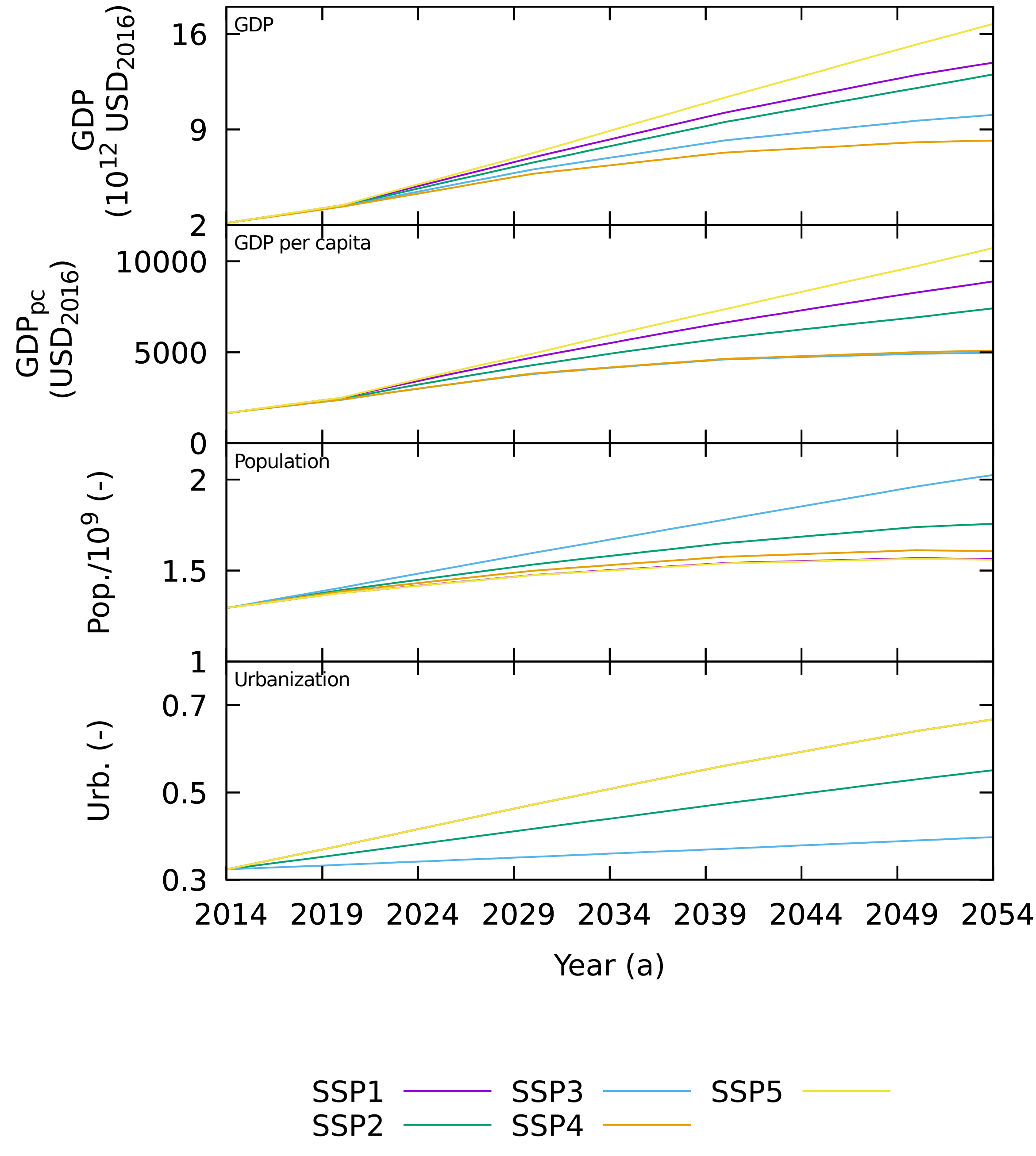


**Figure 6.1:** Quantitative evolution of key scenario drivers of the shared socioeconomic pathways over the model period of this analysis. Per capita GDP is a derived quantity based on GDP and population projections. With respect to urbanization, SSP1, SSP4 and SSP5 exhibit the same trajectory. Underlying data are retrieved from the SSP database, Version 1.1 (`https://tntcat.iiasa.ac.at/SspDb`), and [51].

**Table 6.2:** Base year energy carrier shares for the residential sector derived from [102]. Due to rounding, shares may not add up to 1 (EL: Electricity, NG: Natural gas, LPG: Liquefied petroleum gas, KS: Kerosene, CL: Coal, BM: Biomass, BG: Biogas, S: Solar).

| **End use** | EL | NG | LPG | KS | CL | BM | BG | S |
|---|---|---|---|---|---|---|---|---|
| Rural | | | | | | | | |
| S&W heating | 0.012 | 0.012 | 0.214 | 0.022 | 0.027 | 0.702 | 0.012 | 0.000 |
| Cooking | 0.012 | 0.012 | 0.214 | 0.022 | 0.027 | 0.702 | 0.012 | - |
| Lighting | 0.838 | - | - | 0.162 | - | - | - | - |
| Urban | | | | | | | | |
| S&W heating | 0.002 | 0.002 | 0.747 | 0.047 | 0.020 | 0.179 | 0.002 | 0.000 |
| Cooking | 0.002 | 0.002 | 0.747 | 0.047 | 0.020 | 0.179 | 0.002 | - |
| Lighting | 0.991 | - | - | 0.009 | - | - | - | - |

projection period for the calculation of energy demand in this analysis. Both trajectories are derived through linear interpolation between a historic, modeled population-weighted Indian average and a projected value for 2100 given in [29]. This entails a decrease of heating degree days from $99.8\,°\mathrm{C} \cdot \mathrm{d}$ to $71.5\,°\mathrm{C} \cdot \mathrm{d}$ and an increase of cooling degree days from $3240.3\,°\mathrm{C} \cdot \mathrm{d}$ to $3896.4\,°\mathrm{C} \cdot \mathrm{d}$ during the model period. The exact trajectories for all drivers are given in the energy demand spreadsheet model on the attached CD.

In order to derive projections for the final energy consumption of different energy carriers, and partly also the useful energy consumption of specific end uses, it is necessary to delineate the intensity parameters as defined in Chapter 4 for all scenarios. Whereas a comprehensive analysis of the respective sector would be necessary to derive profoundly reasoned and consistent evolutions for the parameters, the trajectories for this analysis are developed based on simplistic assumptions to explore simplified societal pathways. The exact assumptions and underlying data can be found in the demand projections spreadsheet model.

For the residential sector, the intensity parameters consist of the energy carrier shares $ECS$ and the efficiency factors $EF$. For cooking and lighting, the base year energy carrier shares, i.e., the share of the rural or urban population using a specific energy carrier to satisfy the demand for a particular end use, are derived from household survey data of NSSO [102]. No respective data are readily available for the current use of energy carriers for space & water (S&W) heating. As cooking equipment is widely used for space and water heating among low income households [9], base year values are approximated by the energy carrier shares for cooking. Table 6.2 indicates the energy carrier shares of the base year for each relevant end use in rural and urban areas. The future evolution of the energy carrier shares for cooking is based on linear trajectories to values for the year 2054 derived from [6] and its data on the usage of cooking technologies under various scenarios. Here, correlating scenarios are chosen based on narratives given in Table 6.1. Similar trajectories are assumed for space & water heating while a varying share covered by solar water heaters is added for each of the scenarios. The energy carrier shares derived for the final modeling year 2054 for each of the SSPs are outlined in Table 6.3. For lighting, a linear phase out of kerosene in rural and urban areas until 2025 is assumed across all scenarios.

**Table 6.3:** Energy carrier shares of space & water heating and cooking in the year 2054 for all scenarios. Values are based on scenario data given in [6]. Due to rounding, shares may no add up to 1 (EL: Electricity, NG: Natural gas, LPG: Liquefied petroleum gas, KS: Kerosene, CL: Coal, BM: Biomass, BG: Biogas, S: Solar).

| **End use** | EL | NG | LPG | KS | CL | BM | BG | S |
|---|---|---|---|---|---|---|---|---|
| **SSP1** | | | | | | | | |
| Rural | | | | | | | | |
| S&W heating | 0.265 | 0.055 | 0.274 | 0.000 | 0.000 | 0.151 | 0.105 | 0.150 |
| Cooking | 0.312 | 0.065 | 0.322 | 0.000 | 0.000 | 0.178 | 0.123 | - |
| Urban | | | | | | | | |
| S&W heating | 0.166 | 0.390 | 0.294 | 0.000 | 0.000 | 0.000 | 0.000 | 0.150 |
| Cooking | 0.196 | 0.458 | 0.346 | 0.000 | 0.000 | 0.000 | 0.000 | - |
| **SSP2 & SSP5** | | | | | | | | |
| Rural | | | | | | | | |
| S&W heating | 0.264 | 0.037 | 0.329 | 0.000 | 0.000 | 0.183 | 0.086 | 0.100 |
| Cooking | 0.293 | 0.042 | 0.366 | 0.000 | 0.000 | 0.203 | 0.096 | - |
| Urban | | | | | | | | |
| S&W heating | 0.182 | 0.347 | 0.371 | 0.000 | 0.000 | 0.000 | 0.000 | 0.100 |
| Cooking | 0.202 | 0.386 | 0.412 | 0.000 | 0.000 | 0.000 | 0.000 | - |
| **SSP3 & SSP4** | | | | | | | | |
| Rural | | | | | | | | |
| S&W heating | 0.169 | 0.022 | 0.385 | 0.000 | 0.000 | 0.300 | 0.074 | 0.050 |
| Cooking | 0.177 | 0.024 | 0.406 | 0.000 | 0.000 | 0.316 | 0.078 | - |
| Urban | | | | | | | | |
| S&W heating | 0.139 | 0.361 | 0.450 | 0.000 | 0.000 | 0.000 | 0.000 | 0.050 |
| Cooking | 0.147 | 0.380 | 0.474 | 0.000 | 0.000 | 0.000 | 0.000 | - |

**Table 6.4:** Base year efficiency factors for the residential sector derived from [103] and [104].

| **End use** | **Unit** | EL | NG | LPG | KS | CL | BM | BG | S |
|---|---|---|---|---|---|---|---|---|---|
| S&W heating | - | 0.75 | 0.60 | 0.60 | 0.35 | 0.15 | 0.15 | 0.60 | [1.00] |
| Cooking | - | 0.75 | 0.60 | 0.60 | 0.35 | 0.15 | 0.15 | 0.60 | - |
| Lighting | lm/W | 25.00 | - | - | [0.21] | - | - | - | - |
| Space cooling | - | 1.00 | - | - | - | - | - | - | - |
| Appliances | - | 1.00 | - | - | - | - | - | - | - |

**Table 6.5:** Base year energy carrier intensities for all segments of the industrial, agriculture and service sector based on data from [14], energy service demand proxies derived in Chapter 4 and own assumptions. The energy service demand proxy for the industrial *Other* (arbitrary proxy normalized to 1 for the base year) and the land preparation segment (number of tractors in use) have no units (EL: Electricity, NG: Natural gas, OP: Oil products, CL: Coal, BM: Biofuels and waste).

| **Segment** | **Unit** | EL | NG | OP | CL | BM |
|---|---|---|---|---|---|---|
| Industry | | | | | | |
| IS | TJ/kt | 2.70 | 0.00 | 0.30 | 23.45 | 0.00 |
| CHE | TJ/kt | 6.00 | 0.00 | 7.63 | 2.93 | 0.00 |
| NFM | TJ/kt | 30.82 | 0.00 | 1.99 | 4.97 | 0.00 |
| NMM | TJ/kt | 0.25 | 0.00 | 1.67 | 2.89 | 0.00 |
| PP | TJ/kt | 1.82 | 0.00 | 0.00 | 3.24 | 0.00 |
| OT | $10^6 \cdot$ TJ | 0.97 | 0.28 | 0.20 | 1.24 | 1.29 |
| Agriculture | | | | | | |
| IRR | TJ/1000 ha | 10.88 | 0.00 | 2.95 | 0.00 | 0.00 |
| LP | TJ | 0.00 | 0.00 | 0.06 | 0.00 | 0.00 |
| Service | | | | | | |
| SER | TJ/$10^6$USD$_{2010}$ | 0.22 | 0.02 | 0.04 | 0.16 | 0.21 |

Apart from the energy carrier shares, the efficiency factors *EF*, as introduced in Chapter 4, are decisive for the evolution of residential energy demand. The base year efficiency factors are based on various sources and given in Table 6.4. Their future evolution is based on simple assumptions on the annual efficiency improvement of the device categories and is, as the base year factors, assumed to be equal for rural and urban areas. Values of devices, for which no further improvement is assumed across all scenarios, are given in brackets in Table 6.4. For the remaining technologies, an annual increase of the efficiency factor of 0.002 for space & water heating and cooking, 0.5 lm/W for lighting and 0.005 for space cooling and other appliances is assumed for SSP1 considering a strong effort to foster the uptake of more efficient technologies. For SSP2 and SSP5, considering a slower but steady increase of efficient devices, the efficiency improvements are assumed 50 % of the respective improvement in SSP1, while for SSP3 and SSP4, no efficiency improvement is considered.

The intensity parameters of the industry, agriculture and service sector are derived for each energy carrier and demand segment separately and constitute the consumption of the specific final energy carrier per unit of energy service demand proxy provided. Thus, their evolution incorporates both the efficiency development as well as shifts towards the use of different energy carriers. The base year intensities are developed using the final energy consumption of a particular energy carrier in a demand segment as given by [14] and the base year value of the energy demand proxies as derived in Chapter 4. They are given in Table 6.5. Here, the evolution of the intensities is derived in a very simplistic manner considering potential efficiency changes, the uptake of additional devices and fuel shifts in the respective scenarios. The trajectories are assumed to be similar for all segments. Considering the limited biomass potential and its partially unsustainable usage, the biofuels & waste intensity is assumed to decrease by 70 % in SSP1, 60 % in SSP2 and SSP5, and 50 % in SSP3 and SSP4. For SSP3 and SSP4, anticipating no strong efficiency improvements or fuel shifts, the other intensities

**Table 6.6:** Transport sector modal share of the base year and final years of different scenarios. Base year shares are based on the transport performance derived in Chapter 4 and [6]. Future modal shares are derived from correlating scenario data in [6]. Due to rounding, shares may not add up to 1.

| **Vehicle segment** | 2014 | 2054 Baseline | 2054 Sustainable |
|---|---|---|---|
| Passenger | | | |
| Car | 0.09 | 0.23 | 0.09 |
| 2W | 0.11 | 0.08 | 0.03 |
| 3W | 0.03 | 0.07 | 0.03 |
| Bus | 0.63 | 0.44 | 0.63 |
| Train | 0.13 | 0.15 | 0.20 |
| Airplane | 0.01 | 0.03 | 0.02 |
| Freight | | | |
| LGV | 0.05 | 0.12 | 0.09 |
| HGV | 0.52 | 0.44 | 0.37 |
| Train | 0.27 | 0.28 | 0.38 |
| Airplane | 0.00 | 0.00 | 0.00 |
| Ship | 0.05 | 0.05 | 0.05 |
| Pipeline | 0.11 | 0.11 | 0.11 |

are assumed to stay constant. For SSP2 and SSP5, efficiency improvements are assumed to result in a 5 % decrease of the intensity by the end of the modeling period for all other energy carriers except electricity, for which a constant intensity is assumed due to, e.g., a shift to efficient, electricity-based technologies. A similar but more pronounced development is assumed for SSP1, resulting in an increase of 1 % and decrease of 10 % by 2054 for electricity and the remaining energy carriers, respectively.

For the scenario-based energy demand analysis of this work, the transport sector is only considered with respect to the aggregated energy service demand for passenger and freight travel. Nevertheless, for the transport sector analysis, a separate set of scenarios is introduced in the following section, which is based on assumptions on transport demand trajectories for each vehicle category. In order to calculate the transport demand for specific modes and vehicle types it is necessary to define the evolution of the respective mode shares for different scenarios. The mode share in the base year is derived based on data on the transport performance of the road, rail and air sector discussed in Chapter 4 as well as data on road vehicle performance in [6]. Their future evolution is based on a linear trajectory towards values assumed for the final year of the modeling period of each scenario. Water- and pipeline based freight transport is not considered in the analysis and its share is assumed constant over the modeling period. Apart from a baseline pathway, a scenario with a more sustainable mode share, i.e., a shift to rail and road based public transport, is considered for the analysis. The data for the base year and the final year of both pathways are given in Table 6.6, whereas their consideration for the transport scenarios is discussed in the following section.

## 6.2 Transport Sector Scenarios

The transport sector model described in Chapter 5 can be used in various ways to explore and analyze future pathways of the Indian transport sector with respect to, e.g., a potential decarbonization, import dependence or, if respective emission factors are added, local pollution. This first analysis focuses on the influence of specific aggregated policy efforts towards a decarbonisation of the transport sector. Therefore, the pathways are not based on a comprehensive policy analysis but rather on simplistic assumptions on general policy directions. The scenarios do not try to capture the most likely or optimal pathways of the Indian transport sector, but, instead, serve as exemplary pathways illustrating the influence of respective policy efforts. The *Technological Shift* (TS) scenario entails efforts to increase the use of low-carbon vehicles. As the supply chain of biofuels and hydrogen are currently not profoundly modeled, this analysis focuses on the uptake of battery-based electric vehicles. In addition to technology oriented efforts, the *Technological and Modal Shift* (TMS) scenario involves a political commitment towards a more sustainable share of transport modes as compared to the reference scenario. In order to single out the effects of both policy scenarios towards each other and a baseline scenario, the overall transport service demands are derived from SSP2 for all scenarios. Although a reduction of the motorized transport demand, e.g., through redesigning the built environment [105], can play a substantial role in $CO_2$ emission reductions, it is not further considered in this analysis. Table 6.7 gives an overview over the implemented scenarios and the respective modeling assumptions.

**Table 6.7:** Short narratives and modeling assumptions for the transport sector scenarios.

| **BAU: Business As Usual** |
|---|
| No specific transport policy efforts are undertaken and the sector evolves along historic patterns, general socioeconomic and technological development.<br><br>Modeling assumptions: Based on the data set derived in Chapter 5 and the baseline mode share given in the previous section. |
| **TS: Technological Shift** |
| The implications of carbon emissions are acknowledged and its cost are increasingly valued and considered in the policy-making process. While a decarbonisation of the electricity sector is on the way, transport policies focus on the uptake of low carbon vehicle technologies through, e.g., purchase incentives, whereas no substantial efforts are undertaken to influence the mode choice behavior.<br><br>Modeling assumptions: Apart from BAU assumptions, a carbon tax of 13 $USD_{2016}$ is introduced in 2020 and increases linearly to 200 $USD_{2016}$ in 2045, similar to the *Copenhagen pathway* of the carbon tax in [106]. Moreover, the carbon intensity of the electricity sector is assumed to decrease by 50 % from 979 $gCO_2$-eq/kWh in 2014 to 490 $gCO_2$-eq/kWh in 2054. |
| **TMS: Technological and Modal Shift** |
| In addition to the political commitment of the TS scenario, measures are implemented to foster a more sustainable mode share. Investments are increasingly directed towards public transport infrastructure and incentives for their use are realized.<br><br>Modeling assumptions: Apart from TS assumptions, a mode share trajectory based on the sustainable share presented in the previous section is introduced. |

# 7 Results and Analysis - Exploring Future Pathways

Based on the modeling methodologies outlined in Chapters 4 and 5, the scenarios outlined in the previous chapter are analyzed in the next two sections with respect to the future energy demand and a potential transport sector decarbonization.

## 7.1 Energy Demand Pathways

As mentioned in the introduction, one aim of this thesis is to implement a methodology to derive energy demand projections for India as input to the energy system planning process, in particular for the bottom-up energy system models of the transport and power sector built within the overall research effort. Based on the scenarios introduced in Chapter 6, the developed methodology is applied to establish first scenario-based projections to be used for the long-run energy system models. In the next subsections, the projections of different sectors are presented and shortly analyzed. Except for the transport sector, the analysis is done with respect to the final energy demand, which can serve as input to the power supply sector model. For the transport sector, the energy service demand is considered as it serves as input to the demand sector module introduced in Chapter 5.

### 7.1.1 Residential Sector

Despite the development of a bottom-up model based on various residential energy end uses, this analysis considers mainly the aggregated residential demand, as a definite end use analysis should be based on a thorough calibration and verification of the respective model elements. Figure 7.1 shows the development of final energy demand of the residential sector over the modeling period for all scenarios.

Several common trends can be identified in all scenarios. Final energy demand, driven by economic development and growing population, is increasing throughout all scenarios. Moreover, when looking at the demand for specific energy carriers, two major trends influencing the trajectories can be identified. The demand for electricity, in absolute and relative terms, is increasing drastically in all scenarios. This can be explained by a fuel shift towards electricity and, more important, a substantial diffusion of equipment for space cooling and other electric appliances. In contrast, the demand for biomass is decreasing, whereas the need for alternative fuels, i.e. natural gas, electricity, and partly LPG, is increasing. This development is due to a shift from inefficient biomass-based devices to other, more efficient devices for space & water heating and cooking. Moreover, when considering the data on a different scale, as shown in Figure 7.2, two more general developments can be observed. First, demand for coal and kerosene is phasing out during the scenario period throughout all scenarios. For kerosene, a more pronounced reduction can be observed in the first decade, which can be attributed to the sharp decline in kerosene-based lighting. Second, an increasing use of biogas and solar

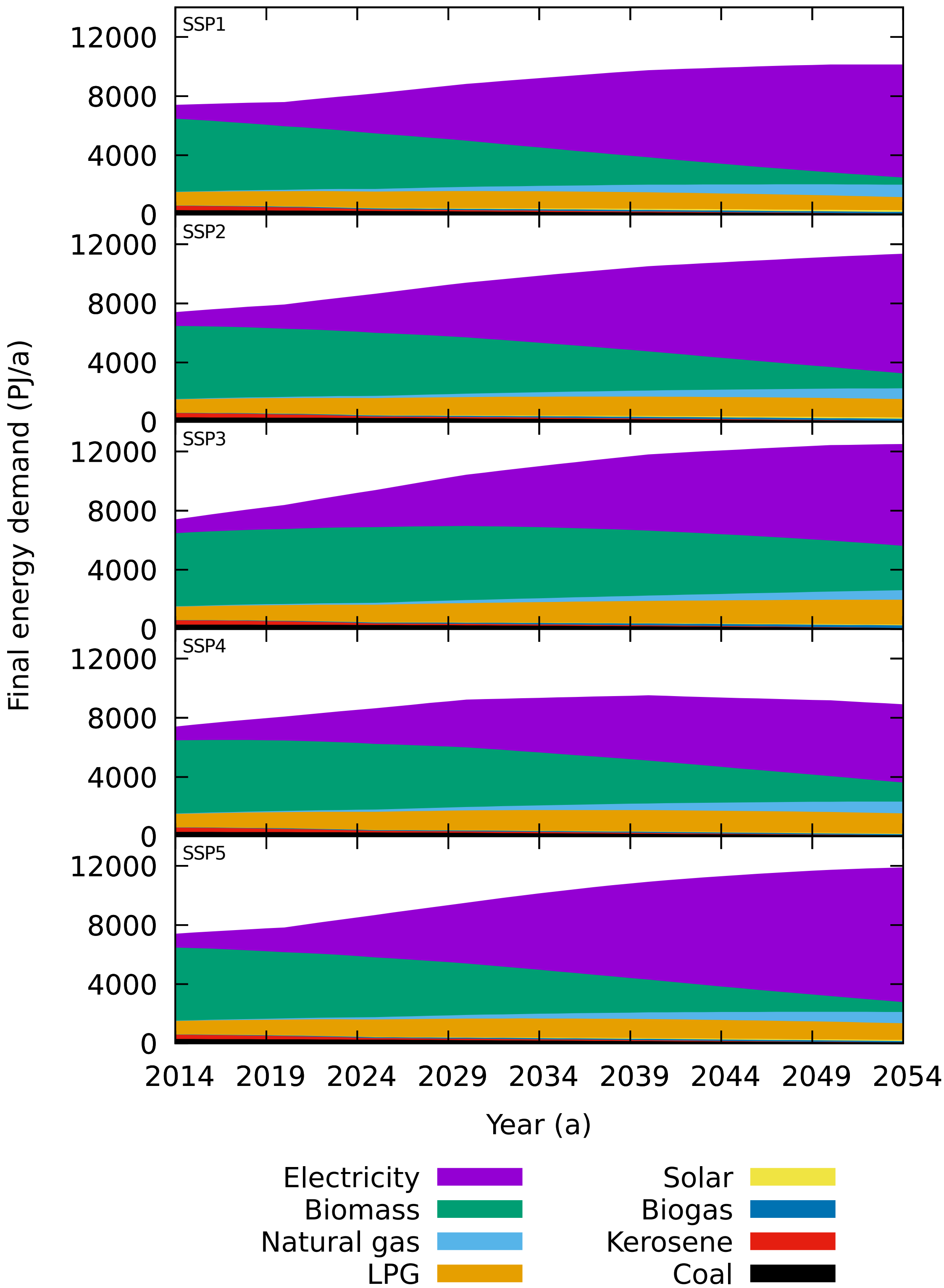


**Figure 7.1:** Final energy demand of the residential sector over the modeling period for all scenarios.

energy can be observed to a varying extent in all scenarios.

A particular strong increase in final energy demand from 7364 PJ/a in 2014 to 12 445 PJ/a (+69 %) and 11 830 PJ/a (+61 %) in 2054 can be observed for SSP3 and SSP5, respectively. This common trajectory is based on diverging characteristics of both scenarios. It can be attributed to the strongly improving economic situation of households in SSP5 and the sharp population growth and only slowing decreasing use of biomass in SSP3. In contrast to the steadily increasing demand in the previous scenarios, SSP1 and SSP4 exhibit a different trajectory. Whereas the final energy demand is flattening towards the end of the modeling period in SSP1, it is slowly decreasing from 2040 onwards in SSP4. Here, the increase in final energy demand from 2014 to 2054 is +37 % and +21 %, respectively. Whereas SSP1 entails the same, limited population growth as SSP5, less pronounced economic development and the diffusion of more energy efficient devices leads to a saturated demand level during the end of the modeling period. In comparison to SSP3, SSP4 exhibits a much lower population growth but also a limited diffusion of electric appliances due to the same restrained improvement of the economic situation of households. In combination with the substitution of the inefficient use of biomass, this results in the decreasing overall final energy demand in SSP4. SSP2 represents a middle way between SSP1 and SSP3 with an increase in final energy demand by +54 % until 2054.

Some of the aforementioned trends can be seen more clearly when removing the influence of population growth and analyzing the per capita demand as shown in Figure 7.3. The decrease in per capita demand for biomass in the scenarios follows corresponding assumptions on the energy carrier shares. Despite equal energy carrier shares for rural and urban areas assumed in SSP3 and SSP4, per capita demand for biomass reduces at a faster pace in SSP4. This can be attributed to the stronger urbanization trend in SSP4, which, in combination with a lower use of biomass in urban than in rural areas, results in a lower demand for biomass. The electricity demand per capita exhibits a sharp increase over the scenario period throughout all scenarios. The magnitude of the increase correlates well with the per capita GDP, and therefore, the economic situation of households, their living space and appliance ownership. It ranges from 3292 MJ/a (915 kWh/a) for SSP4 to 5837 MJ/a (1621 kWh/a) for SSP5 in 2054, as compared to a base year demand of 717 MJ/a (199 kWh/a). This represents a 3.6- and 7.1-fold increase, respectively. Considering the overall per capita final energy demand, it can be seen that, as compared to the absolute demand shown in the previous figure, the removal of the effect of population growth trivially leads to flatter, partly decreasing trajectories.

In order to reveal common demand trends with respect to rural and urban areas as well as the different end uses, these are shortly analyzed based on SSP2. Figure 7.4 shows the final energy demand for different energy carriers in rural and urban areas. The rural demand exhibits a similar pattern as the overall demand shown in the previous figure but, due to the strong urbanization trend and, thus, decreasing rural population, a rather flat overall trajectory. In contrast, the demand in urban areas exhibits a sharp increase due to population growth as well as stronger economic development. The increase is mainly due to the demand for electricity. Moreover, in contrast to rural areas, a considerable share of natural gas can be observed in urban areas. Figure 7.5 highlights another trend with respect to the demand for each end use. Whereas the demand of final energy for space & water heating and cooking is dominant in the beginning of the scenario period, its share decreases drastically during the model period. This can mainly be attributed to two different trends, a shift to more efficient devices, partly using other fuels, as well as an increasing demand caused by appliances, mainly for space cooling.

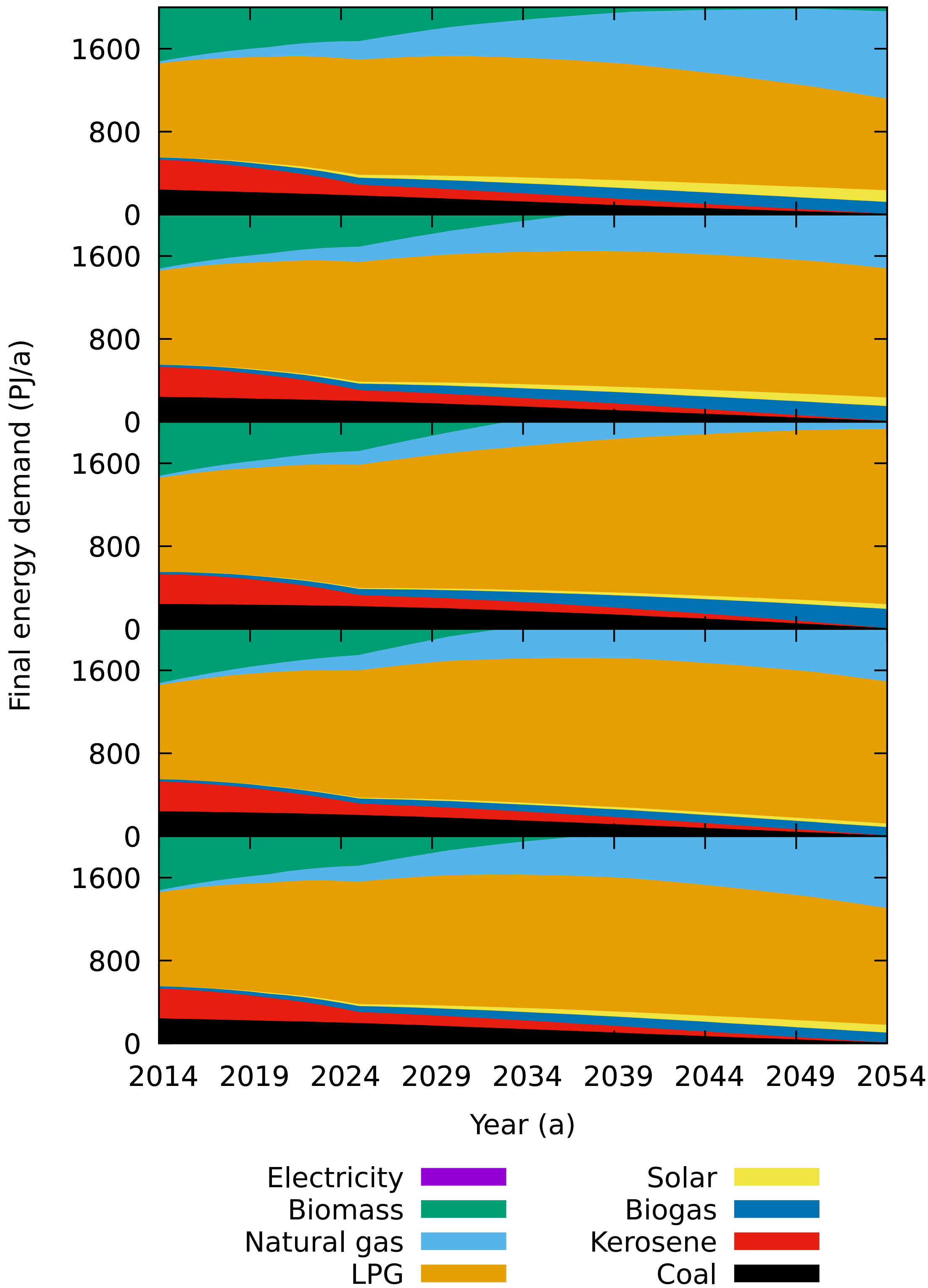


**Figure 7.2:** Final energy demand of the residential sector over the modeling period for all scenarios. The graphs show a cropped and enlarged representation of Figure 7.1.

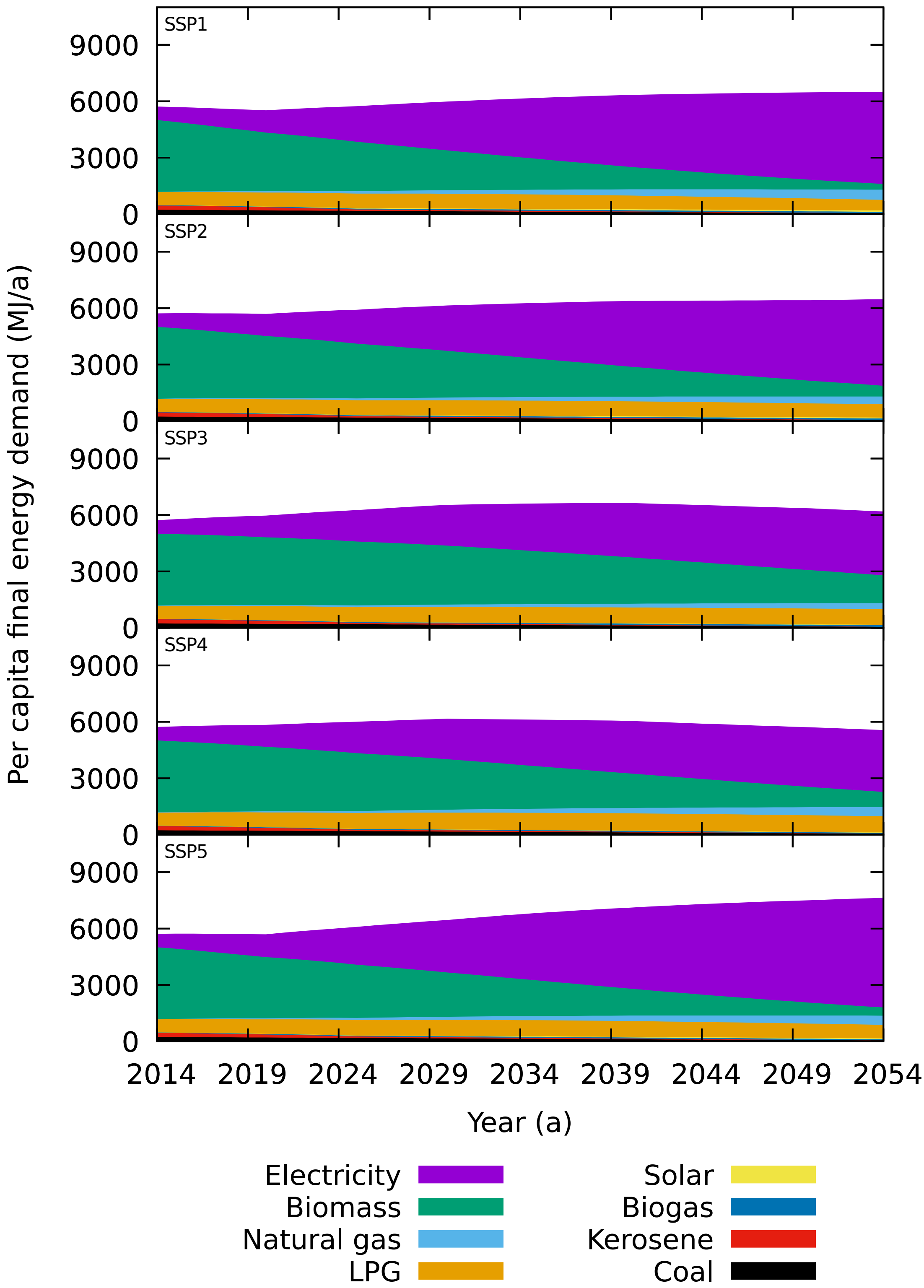


**Figure 7.3:** Per capita final energy demand of the residential sector over the modeling period for all scenarios.

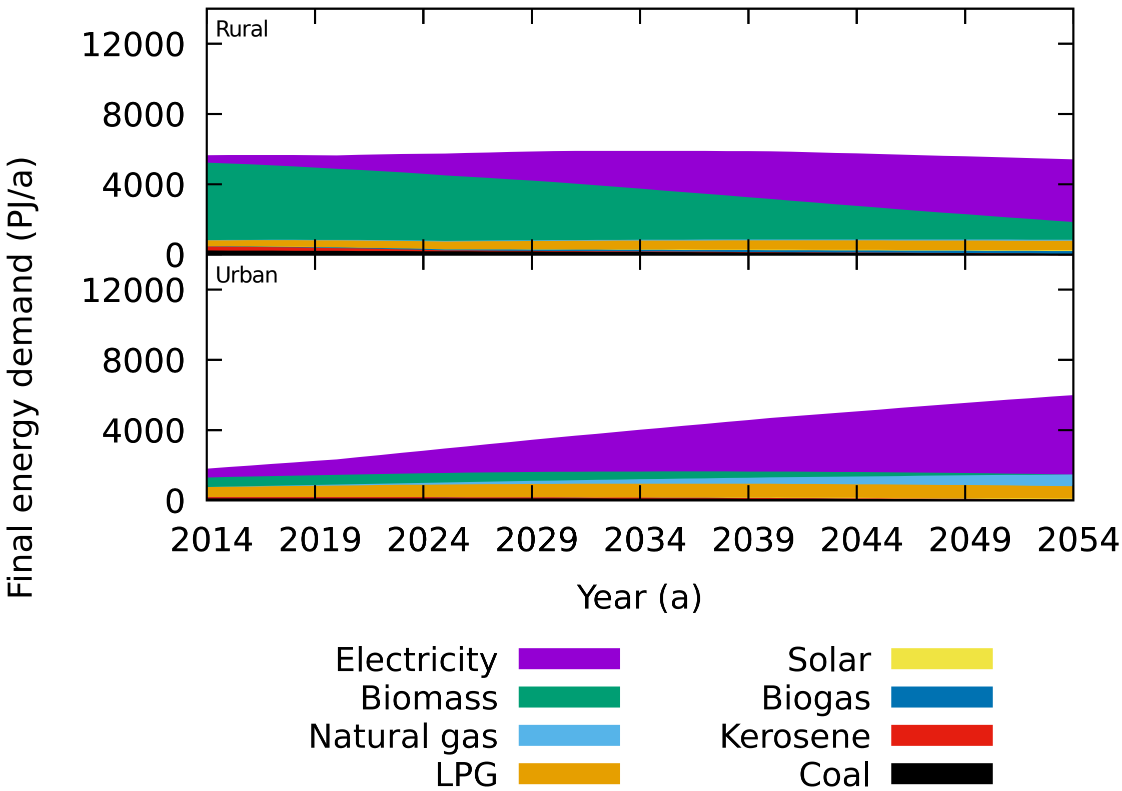


**Figure 7.4:** Final energy demand of the residential sector in SSP2 shown separately for rural and urban areas.

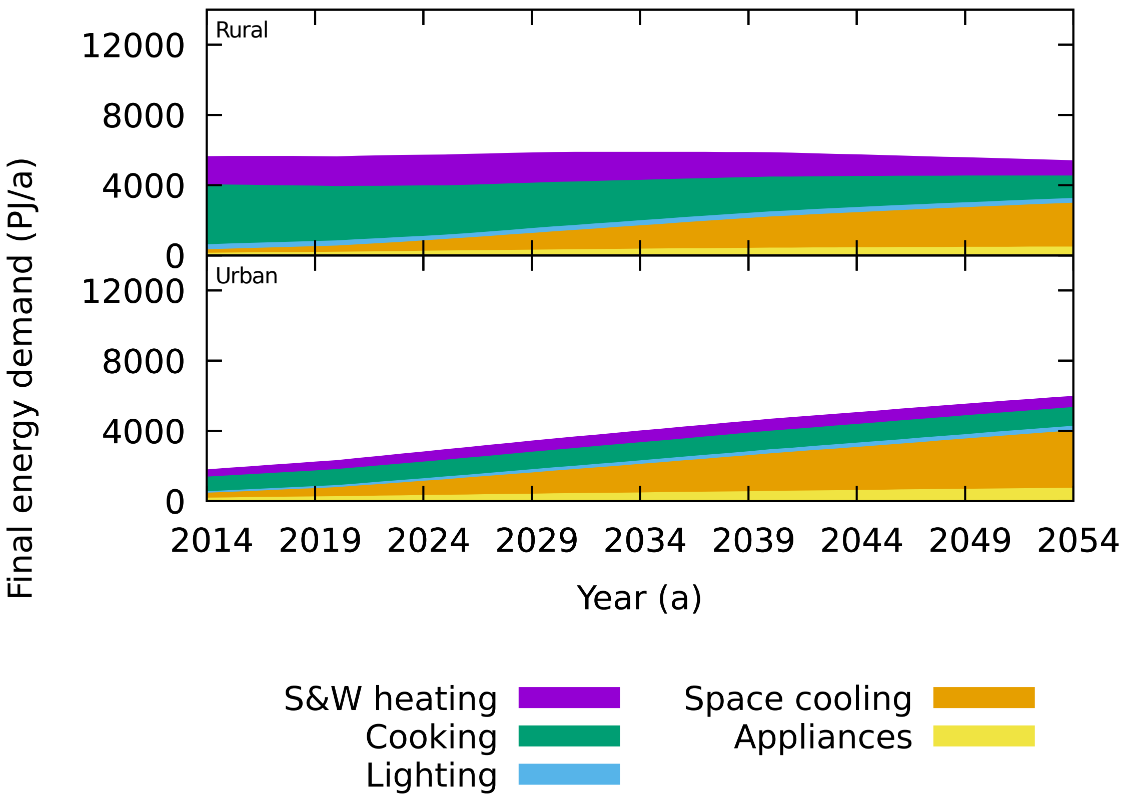


**Figure 7.5:** Final energy demand of the residential sector in SSP2 shown separately for rural and urban areas and split by end use.

### 7.1.2 Industry, Agriculture, Service Sector

The industry, agriculture, and service sectors are based on a common methodology and share the same simplistic scenario assumptions. Therefore, their aggregated final energy demand is compared over all scenarios and a short look is taken on the sector-wise characteristics with respect to scenario SSP2.

Figure 7.6 shows the development of final energy demand over the scenario horizon for all scenarios. In general, a large increase in final energy demand can be observed across all scenarios, where electricity and especially coal are the dominant energy carriers. As defined for the scenarios in the previous chapter, the major development with respect to the share of energy carriers is the decreasing intensity for biofuels in all scenarios. Despite minor differences in the evolution of fuel shares across the scenarios, the major difference is the magnitude of the aggregated demand. As incorporated in the underlying methodology described in Chapter 4, it shows a strong correlation with the evolution of the GDP in the corresponding scenario. It ranges from 9952 PJ/a in 2014 to 33 442 PJ/a for SSP4 and 63 574 PJ/a for SSP5 in 2054.

The characteristic development of the different sectors can be seen in Figure 7.7 showing the evolution of the demand separately for each sector for SSP2. The industry constitutes the major demand sector with around 81 –86 % of the annual demand of all three sectors. It increases 4.3-fold over the modeling period, in comparison to a 5.2-fold increase for the service sector and an increase by 31 % for the agricultural sector. The stronger increase for the service sector can be explained with the increasing importance of the service sector assumed with increasing GDP. Final energy demand in the agricultural sector increases steadily in the first years, before slowly approaching a saturation level in the remaining period. This is due to the assumptions on limited agricultural area and, thus, limited energy service demand for irrigation and agricultural machinery as implemented in the methodology in Chapter 4.

### 7.1.3 Transport Sector

For the transport sector, the energy demand is projected at the level of energy services so it can be used as an input to the developed transport sector module. The per capita motorized transport demand for passengers in pkm and freight in tkm can be seen in Figure 7.8. For both passenger and freight transport similar trends can be observed across all scenarios. The transport demand increases considerably during the first decades of the modeling period before slowly approaching a saturation level. For SSP1, SSP2, and SSP5 the demands reach close to the respective saturation level of 20 000 pkm and 8000 tkm, whereas the limited growth of per capita GDP in SSP3 and SSP4 result in a lower demand level for these scenarios. Figure 7.9 shows the overall transport demand incorporating the diverging population growth rates. It can be seen that in scenarios with stronger and steady population growth, i.e., SSP2 and SSP3, the demand increases relative to the other scenarios and, given the persistent population growth, does not reach a saturation level.

### 7.1.4 Implications and Limitations

In conclusion, the analysis of different energy demand pathways based on diverging societal developments highlights common trends as well as varying characteristics across the scenarios. The diverging magnitude of the demand for specific energy carriers, in particular electricity, can lead to decisive uncertainties in the energy planning process. A profound study of these

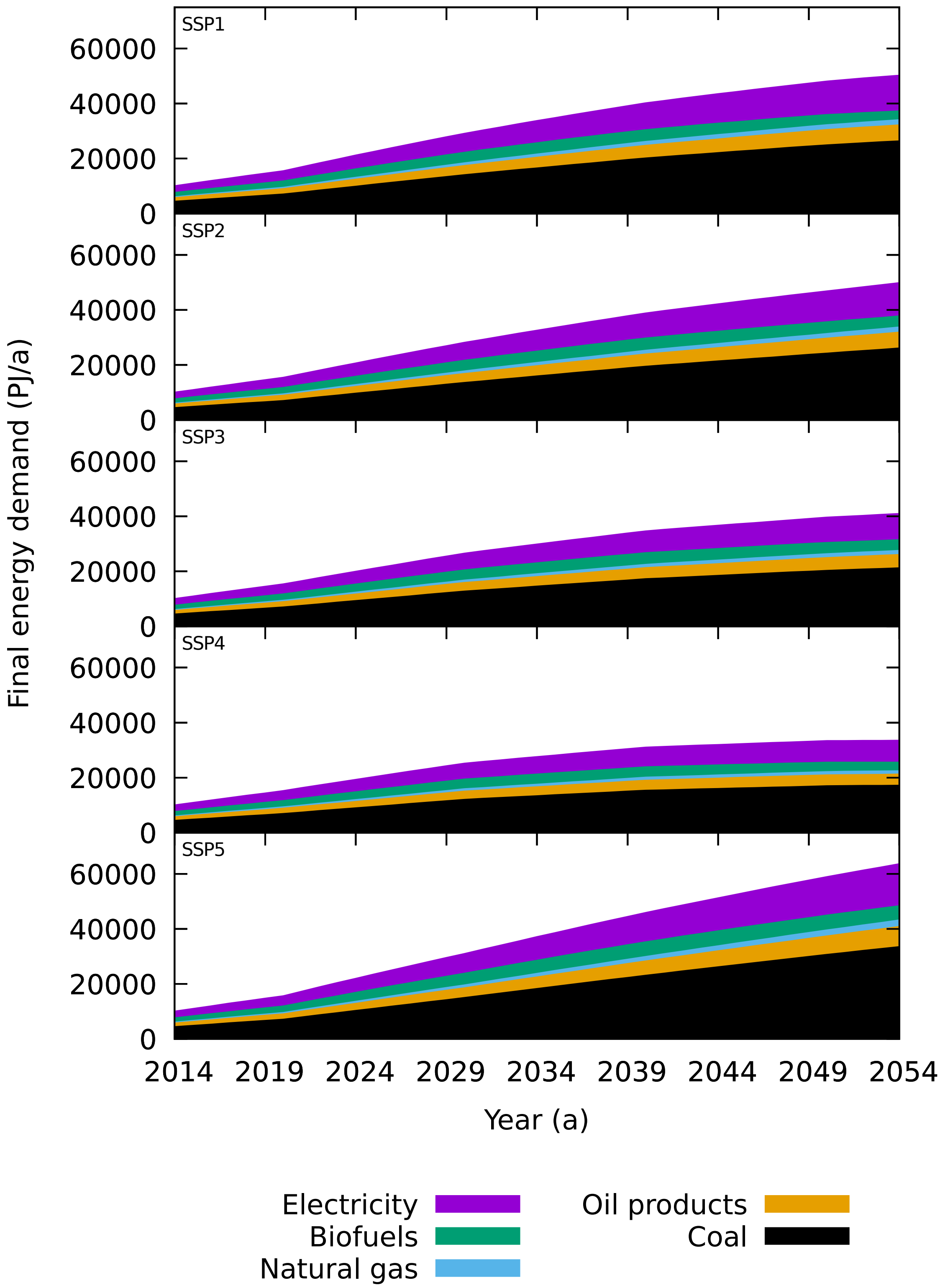


**Figure 7.6:** Aggregated final energy demand of the industry, agriculture and service sector over the modeling period for all scenarios.

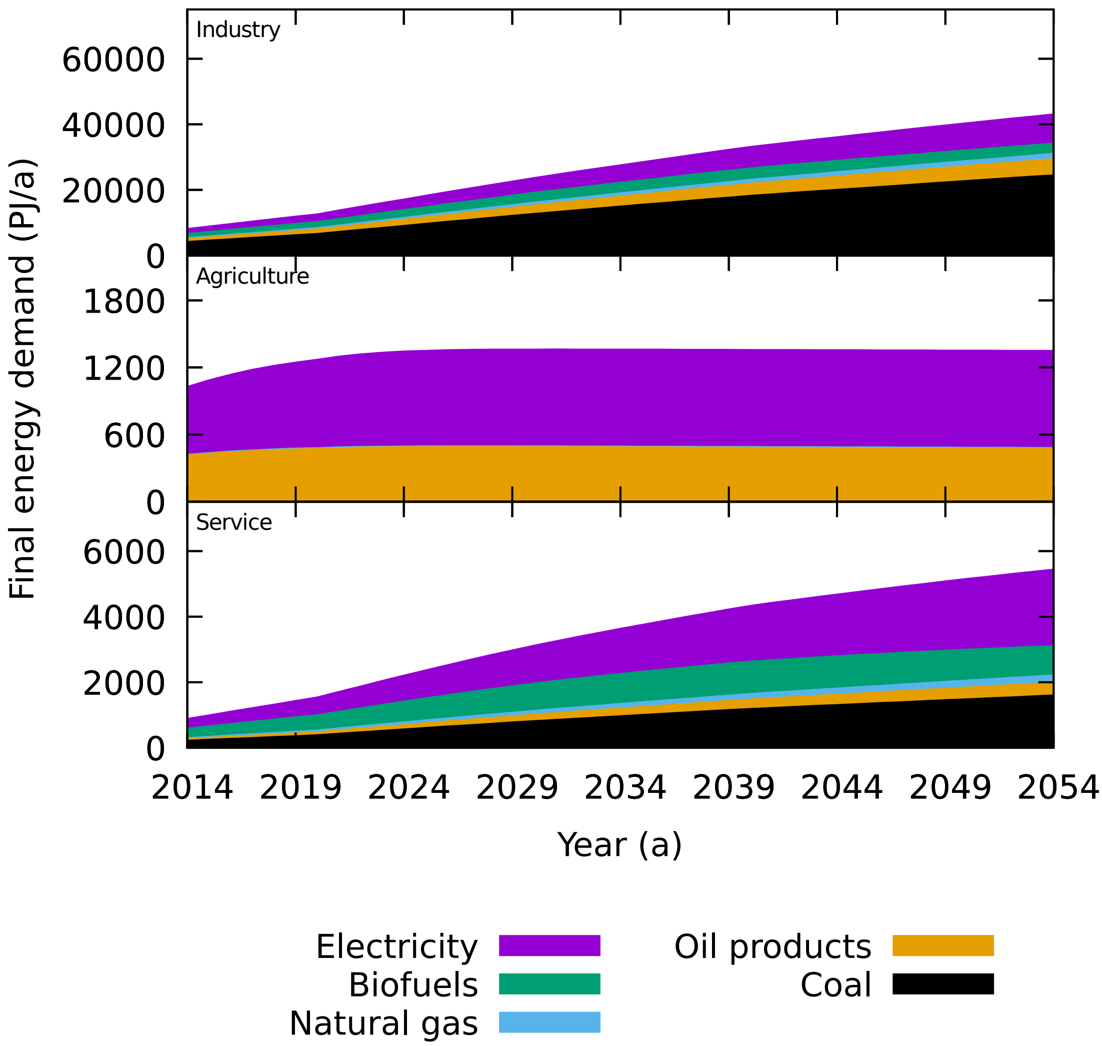


**Figure 7.7:** Separated final energy demand of the industry, agriculture and service sector over the modeling period for SSP2.

uncertainties can be crucial for shaping the future energy system in India. While the chosen scenarios based on the shared socioeconomic pathways give a first impression on potentially distinct characteristics of future demand pathways, their rather simplistic implementation, especially with respect to the industry, agriculture and service sector, hinders a more consistent and complete coverage of the potentially wide scenario space. Moreover, the implementation of the demand model itself, i.e., the quantitative correlations between drivers and demand, and the underlying assumptions are partly subject to considerable uncertainty and demand for a thorough sector-wise qualitative and quantitative demand analysis in future. This is, for example, apparent for the agricultural sector where simplified assumptions on the maximum number of tractors and on limits for the irrigated area have a decisive effect resulting in a quickly stagnating demand.

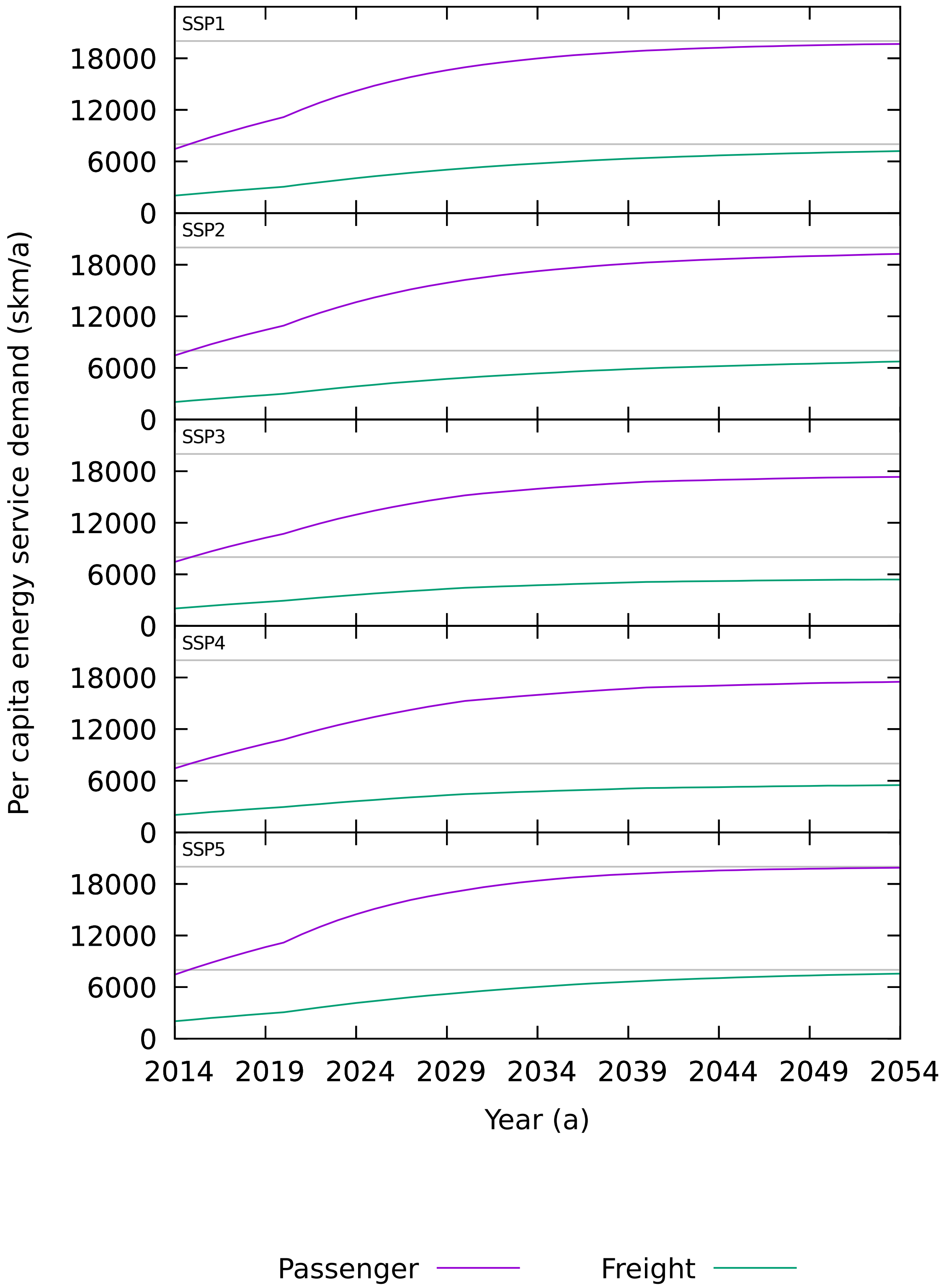


**Figure 7.8:** Per capita energy service demand for passenger and freight transport over the modeling period for all scenarios. skm are *service kilometers*, i.e., pkm and tkm for passenger and freight demand, respectively. The horizontal, grey lines indicate the saturation levels as implemented in the underlying logistic function introduced in Chapter 4.

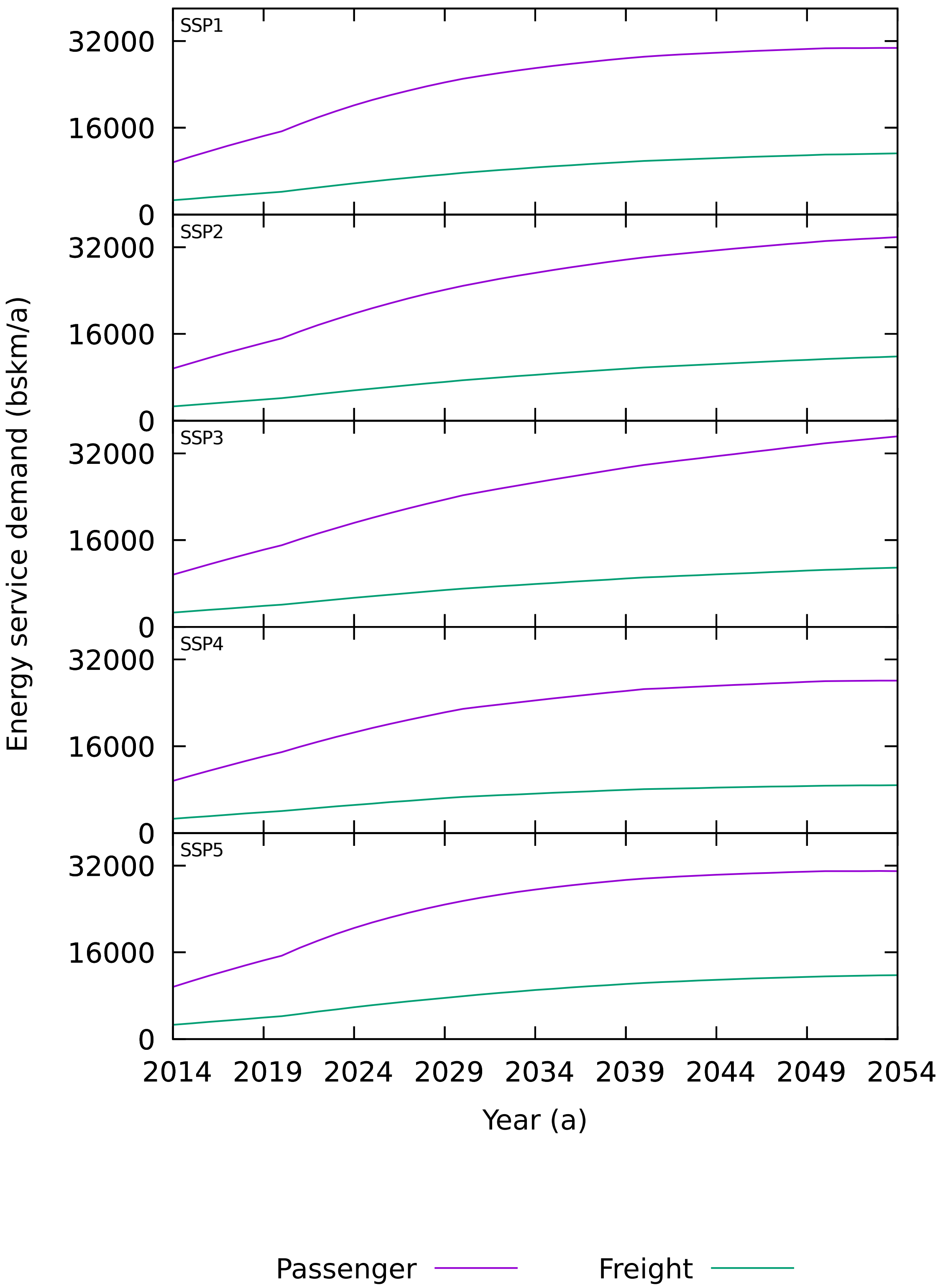


**Figure 7.9:** Energy service demand for passenger and freight transport over the modeling period for all scenarios. bskm are *billion service kilometers*, i.e., bpkm and btkm for passenger and freight demand, respectively.

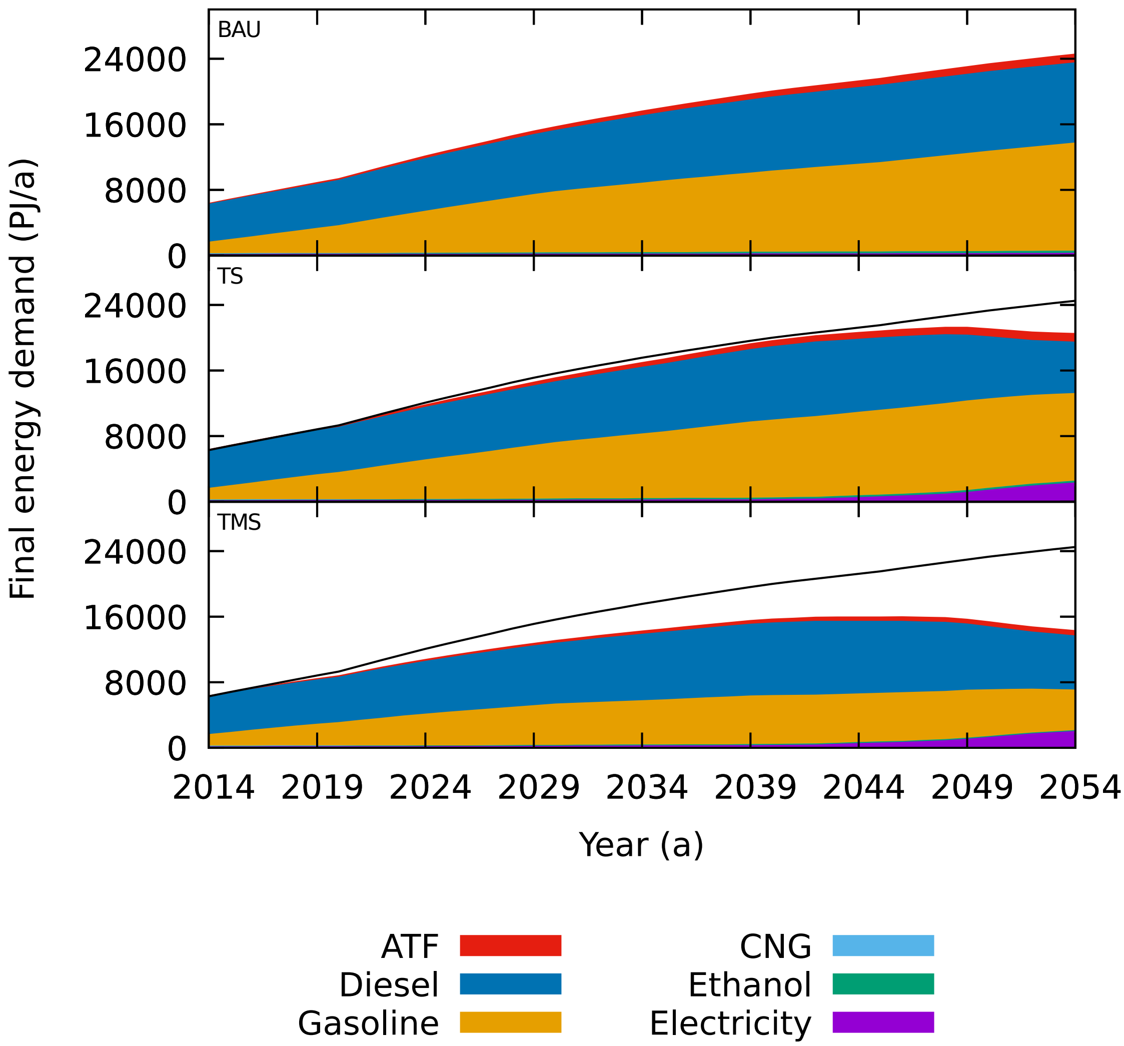


**Figure 7.10:** Final energy demand of the transport sector over the modeling period for all scenarios. The black line in the graphs of the TS and TMS scenario indicate the BAU final energy consumption.

## 7.2 Transport Sector Pathways

Based on scenarios introduced in Chapter 6, three pathways are analyzed in this section in order to get insights into different policy directions towards a decarbonization of the Indian transport system.

The magnitude of final energy demand and consumption of specific energy carriers in the transport sector can give a broad insight into the development of the transport sector. Figure 7.10 shows the consumption of final energy carriers during the modeling period in the transport sector for all scenarios. In the BAU scenario, final energy consumption increases by 289 % during the scenario period, from 6293 PJ in 2014 to 24 498 PJ in 2054. Final energy is mainly consumed in the form of diesel and an increasing share of gasoline. While still a small share of final energy consumption, the usage of aviation turbine fuel increases considerably during the modeling period. Other energy carriers are only used to a very limited extent. The use of compressed natural gas is phasing out during the first half of the modeling period while the use of ethanol is, as explained in Chapter 5, coupled to the consumption of gasoline and, thus, increases steadily. The share of electricity decreases slightly from 0.9 % to 0.8 % during the modeling period. Thus, in absence of major policy efforts in the BAU scenario, the transport sector experiences a drastic increase of final energy consumption in line with the rising transport demand while no major changes in the composition of the fossil fuel dominated energy carrier demand are under way. Final energy consumption in the TS scenario first evolves similarly to the BAU scenario until it starts flattening around 2040 and slightly decreases from 2048 onwards. The diverging overall consumption goes hand in hand with an increase in electricity consumption and a subsequent decrease in the usage of diesel and gasoline. The energy carrier shift is due to the assumed policy effort implemented through a carbon tax in the model. Despite a considerable steep increase of the carbon tax, reaching over 100 $USD_{2016}/ktCO_2$-eq in 2032, it is only in the last decade of the model period that a substantial influence of the policy effort can be observed. Given the currently high carbon intensity of the Indian electricity sector, no low-carbon energy carrier is available in the beginning of the model period. Only the decreasing carbon intensity of the electricity sector, in combination with the technological developments and the carbon tax, yield an uptake of electricity as transport energy carrier. For the TMS scenario, final energy consumption evolves similarly as in the TS scenario but, starting around 2018, stays at a lower level. This indicates that the more sustainable mode share in the TMS scenario entails the use of more efficient vehicles using less final energy while providing the same transport performance. In comparison to the TS scenario, a reduction in aviation turbine fuel and gasoline usage can be observed. This is due to the reduced transport demand covered by airplanes and less efficient private vehicles often running on gasoline, while road- or rail-based public transport, e.g., diesel powered buses, exhibit a higher share.

The dynamics of the final energy consumption discussed in the previous paragraph is based on the specific powertrain technologies deployed in the various vehicle segments. The transport performance of the different technologies are shown for freight transport in Figure 7.11, for private and paratransit passenger transport in Figure 7.12 and for public passenger transport in Figure 7.13. The figures illustrate the underlying technological shifts and effects of scenario policies and are shortly discussed in the following. Generally, the transport performance of each segment trivially follows the respective demand as defined in Chapter 6. Starting with the freight segments of light and heavy goods vehicles, it can be seen that additional demand is met and scrapped conventional compression-ignition engine vehicles (CIEV) are replaced by more efficient hybrid electric vehicles (HEVs) in all scenarios. Similarly, the existing share of CIE trains is slowly replaced by grid electric trains. In line with the increasing share of electricity in the final energy consumption towards the end of the modeling period, further electric goods vehicles are deployed from 2040 onwards in the TS and TMS scenario. First, plug-in hybrid electric vehicles (PHEVs) start to be used. Battery electric vehicle become preferable around 2049 and are then built to meet additional demand and replace scrapped vehicles until their maximum share is reached. The deployment of PHEVs and BEVs shows how, among others, cost reductions of electric vehicle parts, e.g., batteries, and the effect of the carbon tax can lead to an environment in which electricity powered road vehicles are the least-cost option for the model. Considering the transport performance for passenger vehicles for the scenarios shown in Figure 7.12 and Figure 7.13, it can be seen that this development is only present for the freight transport vehicles, for which fuel-related savings due to their comparable long lifetime and high mileage make up for the higher capital cost of PHEVs and BEVs earlier than for other vehicle segments. Otherwise, the passenger segments exhibit similar technological shifts as freight transport. Whereas the existing, negligible shares of CNG powered spark-ignition engine vehicles and BEVs are phased out, other vehicles technologies are, if available, substituted by another, cost optimal technology of each segment. As shown in Figure 7.12, 2-wheelers, for which no hybrid is available in the model, are deployed as SIE

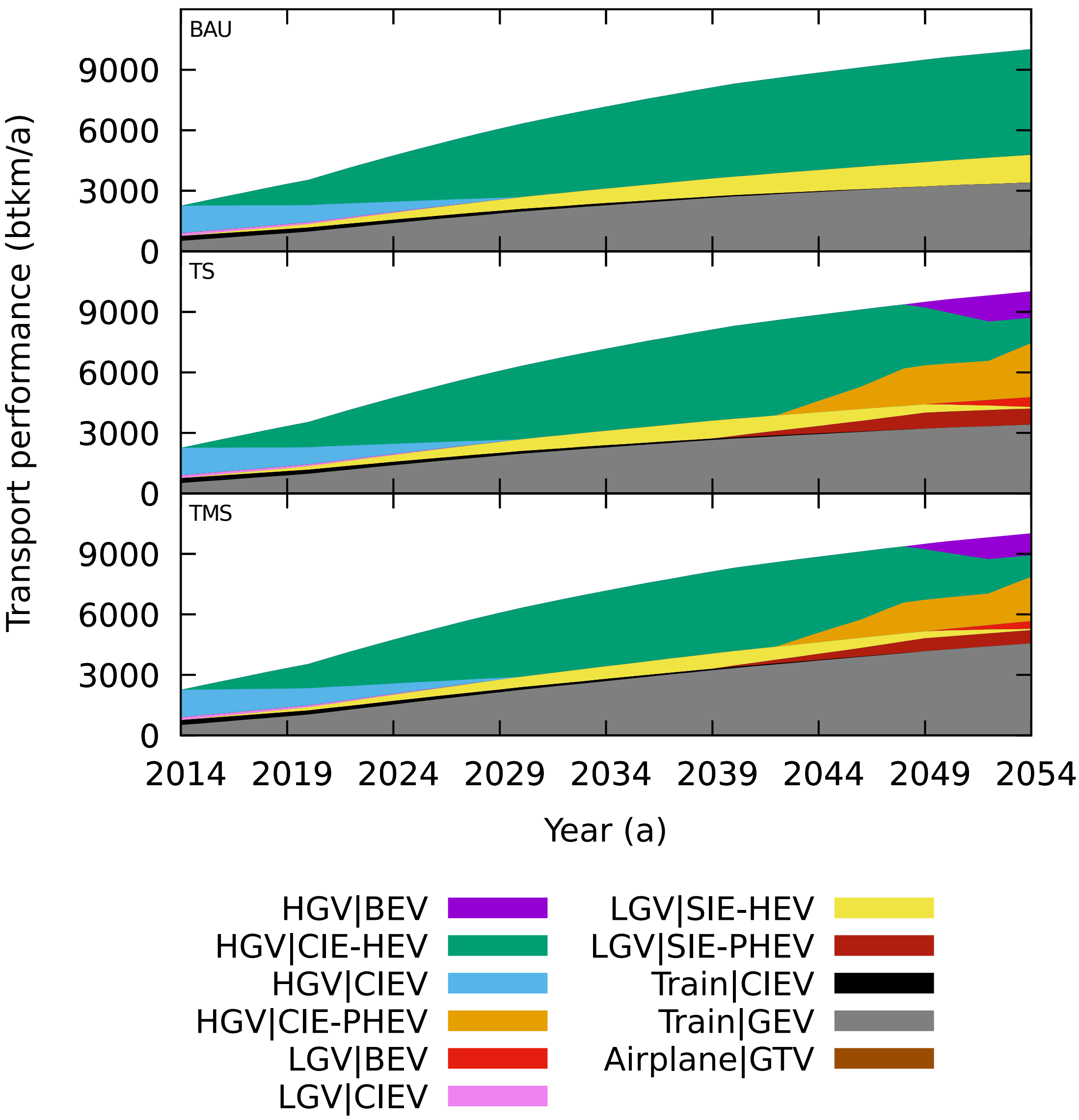


**Figure 7.11:** Transport performance provided by each freight vehicle technology during the modeling period for all scenarios. Vintages of the same road vehicle technology are shown as one aggregated technology.

vehicle throughout the modeling period, whereas SIE-HEVs assume the major role in meeting the demand of the 3-wheeler and car segment. While the shares of deployed powertrain technologies are similar across all scenarios for 2- and 3-wheelers, the introduction of the carbon tax in the TS and TMS scenario causes an earlier shift to car SIE-HEVs as compared to the BAU scenario. Moreover, the figure clearly illustrates the diverging development of the mode share in the TSM scenario, which is exhibiting a reduced demand for private transport and, as can be seen in Figure 7.13, an increased demand for train and bus transport. Whereas no technological choice is available for airplanes, a similar shift from conventional to hybrid diesel buses can be observed across all scenarios. In contrast to the freight rail segment, CIE trains remain the cost optimal technology in the first part of the modeling period and are only starting to be replaced by electric trains in 2036 and 2028 for the BAU, and TS and TMS scenarios, respectively. The diverging behavior with respect to freight trains will be discussed in the next section.

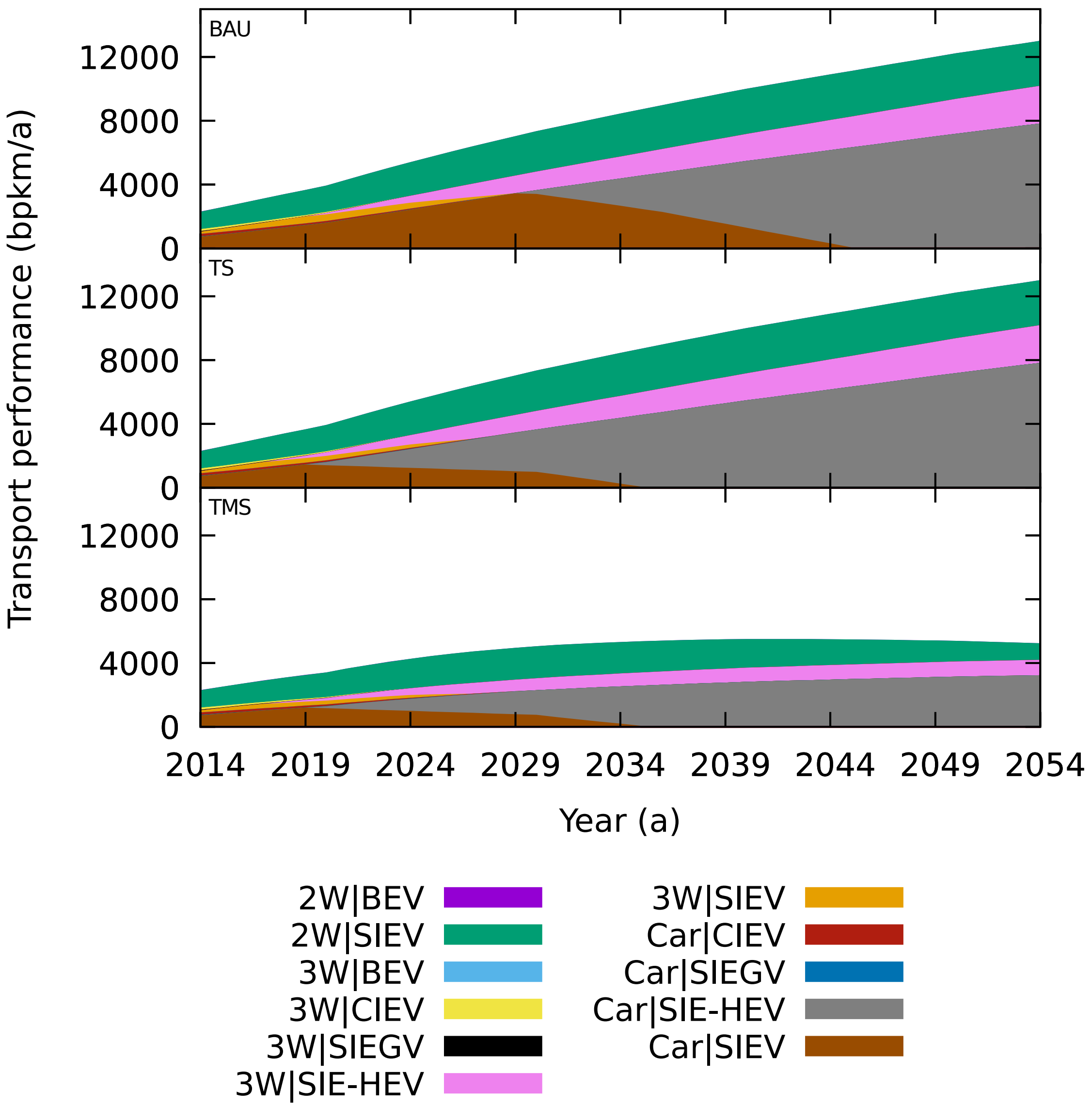


**Figure 7.12:** Transport performance provided by each car, 2- and 3-wheeler motorcycle technology during the modeling period for all scenarios. Vintages of the same road vehicle technology are shown as one aggregated technology.

With respect to a potential decarbonization, the transport sector pathways and respective policy efforts are to be analyzed based on annual $CO_2$-eq emissions resulting from previously discussed consumption and technological developments. The emission pathways for all three scenarios are shown in Figure 7.14. In the BAU scenario, emissions are increasing steadily and are up by +287 % from the base year value in 2054. This highlights the strong fossil fuel and carbon dependency of the Indian transport sector in absence of any decisive political or societal efforts. Annual emissions in the TS scenario closely follow the BAU emissions at a slightly lower level during the first decades of the modeling period. From around 2045 onwards, emissions in the TS scenario further diverge, flatten and reach 89 % of the annual emissions in the BAU scenario in 2054. This falls into line with the uptake of electric vehicles discussed in the previous paragraph. Despite the considerable cost associated to carbon emissions in the TS scenario, only a restrained technological shift is induced and the emission reduction during the modeling period is rather limited. In contrast, the emission pathway of the TMS scenario illustrates the decisive effect of policies influencing the modal share can have on the transport

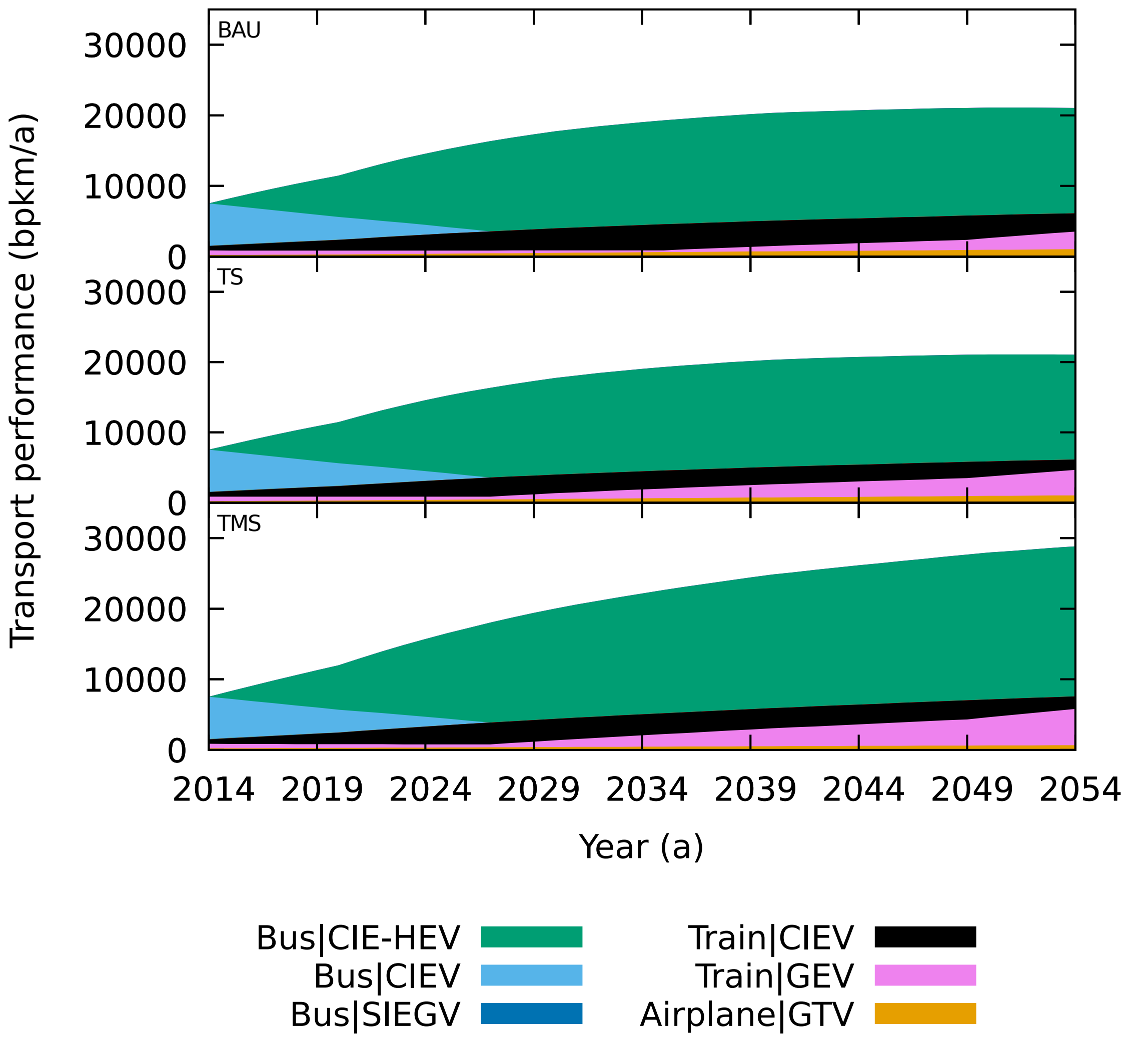


**Figure 7.13:** Transport performance provided by each bus, train and airplane technology during the modeling period for all scenarios. Vintages of the same road vehicle technology are shown as one aggregated technology.

sector emissions. Here, the emissions peak in 2048 and reach 71 % of the BAU emissions in 2054. Cumulative emissions are reduced by 21 % as compared to only 4 % in the TS scenario.

### 7.2.1 Sensitivity Analysis

The optimal deployment of powertrain technologies as discussed in previous paragraphs is based on optimizations using the transport sector model introduced in Chapter 5. Apart from the structural modeling assumptions, the results are, therefore, subject to uncertainties introduced through the input parameters of the model. These include, for example, future costs of batteries or present and future fuel efficiencies of the vehicles of each segment. While acknowledging the need for a comprehensive study of the influence of uncertainties on the results, a first, limited sensitivity analysis is undertaken with respect to the electricity cost and import price for fossil fuels. For that purpose, four additional optimizations are conducted for each scenario, either adjusting the cost of electricity or the cost of all fossil fuel imports by ±30 % and the influence on the emission pathways is studied. Figure 7.15 shows the new emission trajectories for all scenarios. In the first half of the modeling period, the only noticeable effects

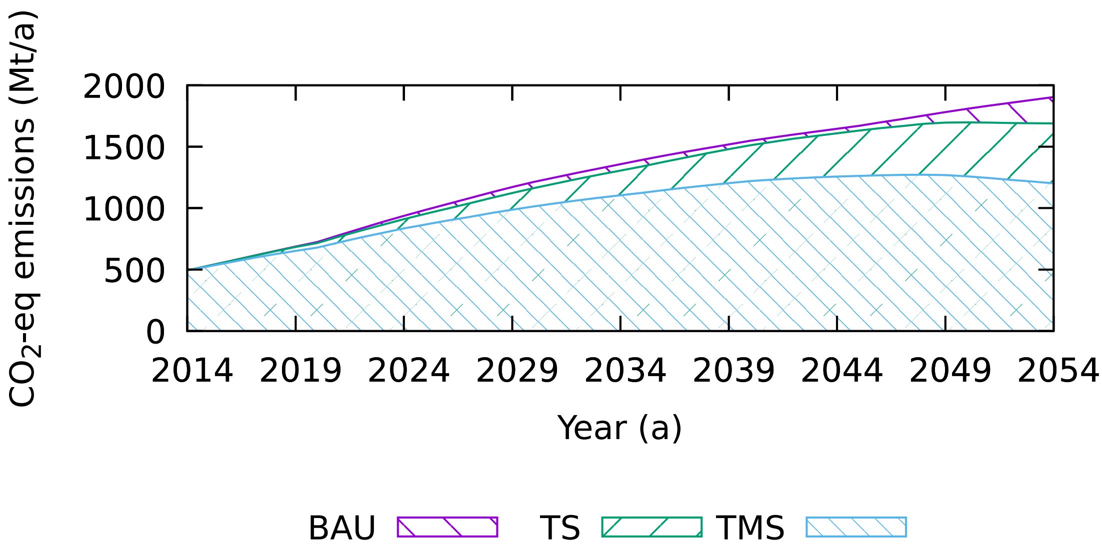


**Figure 7.14:** Annual $CO_2$-eq emissions of the transport sector during the modeling period for all scenarios.

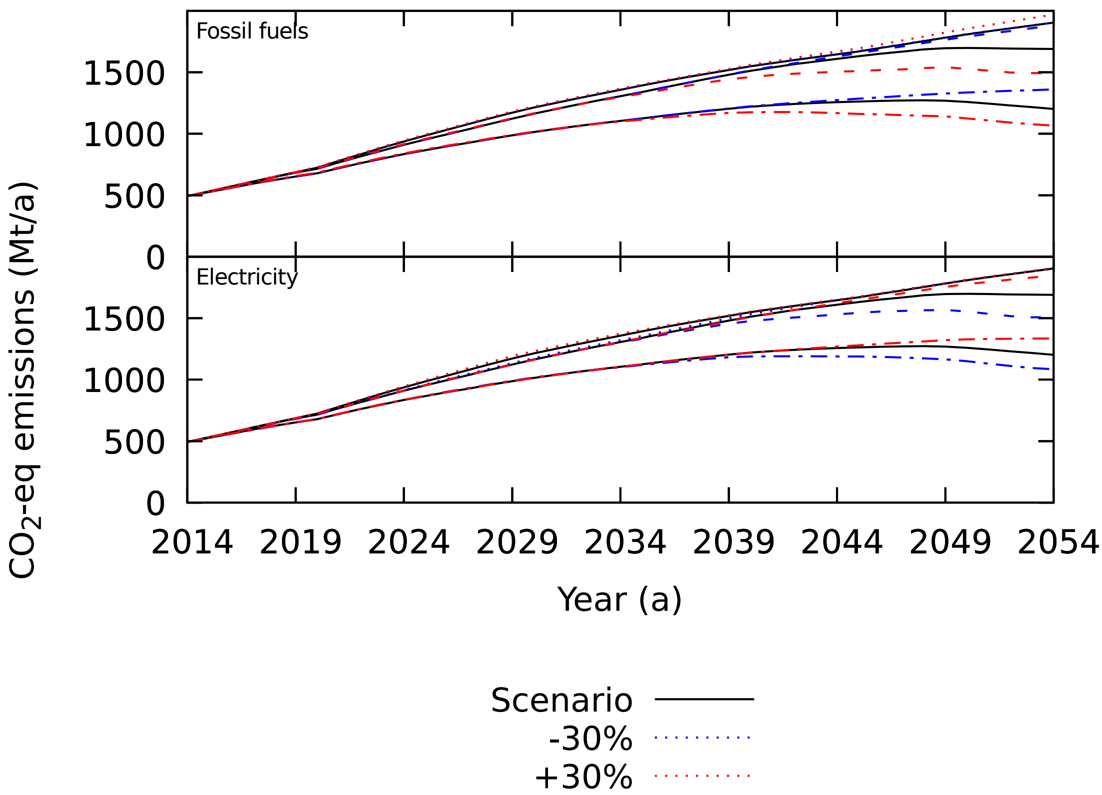


**Figure 7.15:** Annual $CO_2$-eq emissions of the transport sector during the modeling period for all scenarios. Black solid lines show the emissions of the scenarios as shown in Figure 7.14 and dashed/dotted red and blue line show the emission trajectories for increased or decreased fossil fuel (upper graph) and electricity (bottom graph) cost, respectively.

can be seen while increasing the fossil fuel cost in the BAU scenario. The increasing cost here lead to slightly lower emissions due to, e.g., an earlier shift to more efficient mild hybrid cars. For the TS and TMS scenario, a considerable sensitivity can be observed in the second half of the modeling period. Decreased electricity cost or increased fossil fuel cost lead to lower emission based on an increasing electrification of transport vehicles, whereas higher electricity cost and cheaper fossil fuels have the opposite effect. The largest relative uncertainty can be observed for the annual emissions of the TMS scenario which vary between −11 % and +13 % in 2054 while changing the cost of electricity.

Thus, the modeling results for the end of the analyzed period are, to a certain extent, sensitive to the assumptions on the supply cost of energy carriers. Nevertheless, despite the large variation of the cost for this analyses, the emission changes are limited and the major trends and effects derived in the previous section remain valid.

### 7.2.2 Implications and Limitations

To sum up, the analysis gives a first glance on the implications of potential decarbonization efforts with respect to the Indian transport system. Despite the sharp decrease in the carbon intensity of electricity and the quick increase of the carbon tax in the TS scenario, the technological changes and emission reductions compared to the BAU scenario remain limited. This highlights the carbon dependency of the sector and the limited role a technological shift towards electric vehicles can play in $CO_2$ emission reductions before a firm restructuring of the power sector has far advanced. In view of the decisive effects of a more sustainable mode share, the TMS scenario underlines the large potential for policies driving mode choices towards a reduced emission pathway and a more sustainable transport system.

The performance of the model, i.e., its appropriate, though inherently simplified representation of the Indian transport system, is studied with respect to the aggregated final energy consumption in the base year. Whereas IEA reports a final energy consumption of 3557 PJ for domestic road, rail and air based transport in India in 2014 [14], the model yields a consumption of 6293 PJ, an increase of 77 % with respect to the reported data. Even after adjusting for varying usage of lower and higher heating values for the energy carriers, a high discrepancy can be observed. This could partly be caused by uncertainties in the reported data, e.g., the proper representation of kerosene adulteration for the transport sector. Nevertheless, the major reason for the deviation is likely based on the considerable uncertainties with respect to some of the relevant input parameters, e.g., the transport demand and the average occupancy of vehicles. Therefore, a comprehensive calibration of the model is suggested as future work.

Apart from the magnitude of final energy consumption, some further limitations of the results and model are to be addressed. As previously discussed in Chapter 5, the diverse nature of vehicles, infrastructure and actors in the transport sector is difficult to represent in bottom-up energy system models. The model structure can, for example, result in monotonous deployment of a single powertrain technology for a vehicle segment. Here, the model might not conform with an expected mix of technologies but rather shows, based on the model inputs, the idealistic pathway from the viewpoint of a social planner. Moreover, transition dynamics, for instance, with respect to the build up of charging infrastructure for electric vehicles, are not captured in the current model implementation. The model emissions are solely based on the carbon intensity of the energy carrier supply but do not include other emissions, e.g., during the production of the vehicle or the construction of transport infrastructure. Apart from structural limitations, some of the input data are of unknown quality and corrections might lead to varying results. This includes, for example, the diverging fuel efficiencies of freight and passenger trains causing the aforementioned model behavior.

# 8 Conclusions

As part of a collaborative research effort, this work provides quantitative tools to explore and analyze energy demand and transport sector pathways in India. A framework for energy demand projections is developed to generate scenario-based trajectories of the energy demand as input to long-run energy system models and the energy planning process. For the residential sector, the bottom-up energy demand model is considering the different end uses of the sector to better capture expected structural changes. The projections for the industry, agriculture, service, and transport sector are implemented based on simple top-down, econometric models. In a first analysis, the future energy demand is studied with respect to distinct societal pathways. The demand scenarios highlight common trends as well as diverging characteristics of energy demand across potential societal developments. In addition to the projection framework, a long-run energy system model of the Indian transport sector is built. A structure and a data basis for the model is developed and implemented using the open-source modeling framework OSeMOSYS. For a first study, the model is used to analyze the effect of policy directions towards a decarbonization of the Indian transport sector. It underlines the carbon dependency of vehicle technologies within the current energy system and the importance of a modal shift towards a more sustainable transport system in India.

The broad and diverse set of energy demand sectors explicitly covered in this thesis emphasizes the comprehensive nature of the modeling effort. In order to represent the sectors appropriately and to fulfill their purpose, the models require extensive data sets and profound quantitative and qualitative analyses of the technological, socioeconomic and political background. In this light, this work is to be considered as a first step of the overall modeling effort. The current model version and the scenario analyses rely partly on simplistic assumptions and estimates for required data inputs. Nevertheless, the models constitute a suitable foundation and can already yield valuable insights.

In order to further develop the models, it is necessary to review, update and extend the underlying structure and data basis. In particular with respect to the transport sector model, a sustained development of the data basis is crucial to extend the coverage of technologies and transport modes and ensure a well-founded data fundament for future analyses. Moreover, a profound calibration of the model is needed and a link to the power sector model is to be set up.

In conclusion, this thesis establishes energy models to explore energy demand and transport sector pathways and, thus, provides necessary groundwork for further purposeful modeling efforts and well-reasoned energy system planning in India.

# Bibliography


[1] IEA. *Energy and Climate Change: World Energy Outlook Special Report*. Tech. rep. International Energy Agency, 2015. URL: https://www.iea.org/publications/freepublications/publication/WEO2015SpecialReportonEnergyandClimateChange.pdf (visited on 2017-11-27).

[2] Government of India. *India's Intended Nationally Determined Contribution*. 2015. URL: http://www4.unfccc.int/submissions/INDC/Published%20Documents/India/1/INDIA%20INDC%20TO%20UNFCCC.pdf (visited on 2017-11-27).

[3] Md. Mizanur Rahman, Jukka V. Paatero, and Risto Lahdelma. *Evaluation of choices for sustainable rural electrification in developing countries: A multicriteria approach*. In: *Energy Policy* 59 (Aug. 2013), pp. 589–599. ISSN: 0301-4215. DOI: 10.1016/j.enpol.2013.04.017. URL: https://www.sciencedirect.com/science/article/pii/S0301421513002565 (visited on 2017-11-14).

[4] Eoin Ó Broin and Céline Guivarch. *Transport infrastructure costs in low-carbon pathways*. In: *Transportation Research Part D: Transport and Environment* 55.Supplement C (Aug. 2017), pp. 389–403. ISSN: 1361-9209. DOI: 10.1016/j.trd.2016.11.002. URL: http://www.sciencedirect.com/science/article/pii/S1361920916301997 (visited on 2017-11-14).

[5] The Energy and Resources Institute, ed. *National energy map for India: technology vision, 2030*. New Delhi: Energy and Resources Institute : Office of the Principal Scientific Adviser, Govt. of India, 2006. ISBN: 978-81-7993-099-1.

[6] NITI Aayog. *India Energy Security Scenarios 2047*. 2015. URL: http://indiaenergy.gov.in/iess/docs/IESS_Version2.2.xlsx (visited on 2017-08-31).

[7] Subash Dhar and Priyadarshi R. Shukla. *Low carbon scenarios for transport in India: Co-benefits analysis*. en. In: *Energy Policy* 81 (June 2015), pp. 186–198. ISSN: 03014215. DOI: 10.1016/j.enpol.2014.11.026. URL: http://linkinghub.elsevier.com/retrieve/pii/S030142151400634X (visited on 2017-04-21).

[8] Subash Dhar, Minal Pathak, and Priyadarshi R. Shukla. *Electric vehicles and India's low carbon passenger transport: a long-term co-benefits assessment*. en. In: *Journal of Cleaner Production* 146 (Mar. 2017), pp. 139–148. ISSN: 09596526. DOI: 10.1016/j.jclepro.2016.05.111. URL: http://linkinghub.elsevier.com/retrieve/pii/S0959652616305832 (visited on 2017-04-21).

[9] Bas J. van Ruijven et al. *Model projections for household energy use in India*. In: *Energy Policy*. Clean Cooking Fuels and Technologies in Developing Economies 39.12 (Dec. 2011), pp. 7747–7761. ISSN: 0301-4215. DOI: 10.1016/j.enpol.2011.09.021. URL: http://www.sciencedirect.com/science/article/pii/S0301421511007105 (visited on 2017-04-24).

[10] Vaibhav Chaturvedi et al. *Long term building energy demand for India: Disaggregating end use energy services in an integrated assessment modeling framework*. In: *Energy Policy* 64 (Jan. 2014), pp. 226–242. ISSN: 0301-4215. DOI: 10.1016/j.enpol.2012.11.021. URL: http://www.sciencedirect.com/science/article/pii/S030142151200986X (visited on 2017-04-24).

[11] IEA. *India Energy Outlook*. Tech. rep. International Energy Agency, 2015. URL: https://www.iea.org/publications/freepublications/publication/IndiaEnergyOutlook_WEO2015.pdf (visited on 2017-11-27).

[12] NITI Aayog. *Draft National Energy Policy (Version as on 27.06.2017)*. 2017. URL: http://indiaenergy.gov.in/wp-content/uploads/2017/10/Draft-National-Energy-Policy.pdf (visited on 2017-11-19).

[13] NTDPC. *India Transport Report: Moving India to 2032*. OCLC: ocn885078356. New Delhi: Routledge, 2014. ISBN: 978-1-138-79598-3.

[14] IEA. *Energy Balance Flows: India - Final Consumption*. 2017. URL: http://www.iea.org/Sankey/#?c=India&s=Final%20consumption (visited on 2017-10-01).

[15] B. R. Gurjar, Khaiwal Ravindra, and Ajay Singh Nagpure. *Air pollution trends over Indian megacities and their local-to-global implications*. In: *Atmospheric Environment* 142.Supplement C (Oct. 2016), pp. 475–495. ISSN: 1352-2310. DOI: 10.1016/j.atmosenv.2016.06.030. URL: http://www.sciencedirect.com/science/article/pii/S1352231016304630 (visited on 2017-11-09).

[16] T. V. Ramachandra and Shwetmala. *Emissions from India's transport sector: Statewise synthesis*. In: *Atmospheric Environment* 43.34 (Nov. 2009), pp. 5510–5517. ISSN: 1352-2310. DOI: 10.1016/j.atmosenv.2009.07.015. URL: http://www.sciencedirect.com/science/article/pii/S1352231009005871 (visited on 2017-11-09).

[17] Atom Mirakyan and Roland De Guio. *Integrated energy planning in cities and territories: A review of methods and tools*. In: *Renewable and Sustainable Energy Reviews* 22.Supplement C (June 2013), pp. 289–297. ISSN: 1364-0321. DOI: 10.1016/j.rser.2013.01.033. URL: http://www.sciencedirect.com/science/article/pii/S1364032113000646 (visited on 2017-11-10).

[18] João Pedro Gouveia, Patrícia Fortes, and Júlia Seixas. *Projections of energy services demand for residential buildings: Insights from a bottom-up methodology*. In: *Energy*. Asia-Pacific Forum on Renewable Energy 2011 47.1 (Nov. 2012), pp. 430–442. ISSN: 0360-5442. DOI: 10.1016/j.energy.2012.09.042. URL: http://www.sciencedirect.com/science/article/pii/S0360544212007207 (visited on 2017-04-27).

[19] L. Suganthi and Anand A. Samuel. *Energy models for demand forecasting - A review*. en. In: *Renewable and Sustainable Energy Reviews* 16.2 (Feb. 2012), pp. 1223–1240. ISSN: 13640321. DOI: 10.1016/j.rser.2011.08.014. URL: http://linkinghub.elsevier.com/retrieve/pii/S1364032111004242 (visited on 2017-04-20).

[20] Subhes C Bhattacharyya and Govinda R Timilsina. *Energy demand models for policy formulation: a comparative study of energy demand models*. English. Tech. rep. OCLC: 793541127. Washington, D.C.: World Bank, Development Research Group, Environment and Energy Team, 2009.

[21] Subhes C. Bhattacharyya and Govinda R. Timilsina. *A review of energy system models*. en. In: *International Journal of Energy Sector Management* 4.4 (Nov. 2010), pp. 494–518. ISSN: 1750-6220. DOI: 10.1108/17506221011092742. URL: http://www.emeraldinsight.com/doi/10.1108/17506221011092742 (visited on 2017-11-22).

[22] Patrícia Fortes et al. *Integrated technological-economic modeling platform for energy and climate policy analysis*. In: *Energy* 73 (Aug. 2014), pp. 716–730. ISSN: 0360-5442. DOI: 10.1016/j.energy.2014.06.075. URL: http://www.sciencedirect.com/science/article/pii/S0360544214007749 (visited on 2017-04-21).

[23] Sabine Messner and Manfred Strubegger. *User's Guide for MESSAGE III*. Tech. rep. WP-95-069. IIASA, 1995. URL: http://pure.iiasa.ac.at/4527/1/WP-95-069.pdf (visited on 2017-11-20).

[24] Richard Loulou et al. *Documentation for the TIMES Model: Part I*. 2005. URL: http://iea-etsap.org/docs/TIMESDoc-Intro.pdf (visited on 2017-11-20).

[25] Mark Howells et al. *OSeMOSYS: The Open Source Energy Modeling System*. en. In: *Energy Policy* 39.10 (Oct. 2011), pp. 5850–5870. ISSN: 03014215. DOI: 10.1016/j.enpol.2011.06.033. URL: http://linkinghub.elsevier.com/retrieve/pii/S0301421511004897 (visited on 2017-04-20).

[26] Joseph DeCarolis et al. *Formalizing best practice for energy system optimization modelling*. In: *Applied Energy* 194 (May 2017), pp. 184–198. ISSN: 0306-2619. DOI: 10.1016/j.apenergy.2017.03.001. URL: http://www.sciencedirect.com/science/article/pii/S0306261917302192 (visited on 2017-07-07).

[27] Lee Schipper et al. *INDICATORS OF ENERGY USE AND CARBON EMISSIONS: Explaining the Energy Economy Link*. In: *Annual Review of Energy and the Environment* 26.1 (2001), pp. 49–81. DOI: 10.1146/annurev.energy.26.1.49. URL: https://doi.org/10.1146/annurev.energy.26.1.49 (visited on 2017-09-24).

[28] United Nations Centre for Human Settlements, ed. *An urbanizing world: global report on human settlements, 1996*. Oxford ; New York: Oxford University Press for the United Nations Centre for Human Settlements (HABITAT), 1996. ISBN: 0-19-823346-9.

[29] Morna Isaac and Detlef P. van Vuuren. *Modeling global residential sector energy demand for heating and air conditioning in the context of climate change*. In: *Energy Policy* 37.2 (Feb. 2009), pp. 507–521. ISSN: 0301-4215. DOI: 10.1016/j.enpol.2008.09.051. URL: http://www.sciencedirect.com/science/article/pii/S0301421508005168 (visited on 2017-05-03).

[30] Jiyong Eom et al. *China's building energy demand: Long-term implications from a detailed assessment*. In: *Energy*. Energy and Exergy Modelling of Advance Energy Systems 46.1 (Oct. 2012), pp. 405–419. ISSN: 0360-5442. DOI: 10.1016/j.energy.2012.08.009. URL: http://www.sciencedirect.com/science/article/pii/S0360544212006214 (visited on 2017-04-28).

[31] National Sample Survey Office (India). *Housing Condition in India*. 2004. URL: http://www.mospi.gov.in/sites/default/files/publication_reports/488_final.pdf (visited on 2017-11-27).

[32] Vassilis Daioglou, Bas J. van Ruijven, and Detlef P. van Vuuren. *Model projections for household energy use in developing countries*. In: *Energy*. 7th Biennial International Workshop "Advances in Energy Studies" 37.1 (Jan. 2012), pp. 601–615. ISSN: 0360-5442. DOI: 10.1016/j.energy.2011.10.044. URL: http://www.sciencedirect.com/science/article/pii/S0360544211007110 (visited on 2017-05-03).

[33] Olivia Guerra Santin, Laure Itard, and Henk Visscher. *The effect of occupancy and building characteristics on energy use for space and water heating in Dutch residential stock*. In: *Energy and Buildings* 41.11 (Nov. 2009), pp. 1223–1232. ISSN: 0378-7788. DOI: 10.1016/j.enbuild.2009.07.002. URL: http://www.sciencedirect.com/science/article/pii/S0378778809001388 (visited on 2017-09-25).

[34] Dishna Schwarz, Elmar Dimpl, and George C. Bandlamudi. *Lighting Technologies*. In: *InfoGate, GTZ, Editor* (2005). URL: http://www.uni-oldenburg.de/fileadmin/user_upload/physik-ppre/download/Downloads/Lighting_Technologies_1.pdf (visited on 2017-06-01).

[35] Evan Mills. *Technical and economic performance analysis of kerosene lamps and alternative approaches to illumination in developing countries.* 2003. URL: http://evanmills.lbl.gov/pubs/pdf/offgrid-lighting.pdf (visited on 2017-06-01).

[36] Stephane de la Rue de Can, Michael McNeil, and Jayant Sathaye. *India Energy Outlook: End Use Demand in India to 2020.* In: *Lawrence Berkeley National Laboratory* (2009). URL: https://ies.lbl.gov/sites/all/files/lbnl-1751e.pdf (visited on 2017-11-27).

[37] National Sample Survey Office (India). *Household Consumption of Various Goods and Services in India 2011-12.* 2014. URL: http://mospi.nic.in/sites/default/files/publication_reports/Report_no558_rou68_30june14.pdf (visited on 2017-11-27).

[38] Mindaugas Jakubcionis and Johan Carlsson. *Estimation of European Union residential sector space cooling potential.* In: *Energy Policy* 101 (Feb. 2017), pp. 225–235. ISSN: 0301-4215. DOI: 10.1016/j.enpol.2016.11.047. URL: http://www.sciencedirect.com/science/article/pii/S030142151630653X (visited on 2017-06-03).

[39] Nihar Shah, Amol Phadke, and Paul Waide. *Cooling the planet: opportunities for deployment of superefficient room air conditioners.* In: (2013). URL: http://escholarship.org/uc/item/253583c5.pdf (visited on 2017-06-04).

[40] Central Electricity Authority (India). *Load Generation Balance Report 2010-11.* 2010. URL: http://www.cea.nic.in/reports/annual/lgbr/lgbr-2010.pdf (visited on 2017-11-20).

[41] NITI Aayog. *India Energy Dashboard: Gas Supply.* 2017. URL: http://indiaenergy.gov.in/edm/#gasSupply (visited on 2017-11-20).

[42] Ministry of Agriculture And Farmer's Welfare (India). *Agricultural Census (1970-71 to 2010-11).* URL: http://agcensus.nic.in/ (visited on 2017-06-15).

[43] Food and Agricultural Organization of the United Nations. *FAOSTAT.* URL: http://www.fao.org/faostat/en/#home (visited on 2017-11-20).

[44] World Steel Association. *Steel Statistical Yearbook 1990.* URL: https://www.worldsteel.org/en/dam/jcr:706777d8-1453-406b-aa75-1128abf14d1c/Steel+statistical+yearbook+1990.pdf (visited on 2017-06-15).

[45] World Steel Association. *Steel Statistical Yearbook 1999.* URL: https://www.worldsteel.org/en/dam/jcr:051f894c-fab0-40bd-bacd-2c089438f409/Steel+statistical+yearbook+1999.pdf (visited on 2017-06-15).

[46] World Steel Association. *Steel Statistical Yearbook 2009.* URL: https://www.worldsteel.org/en/dam/jcr:818a3c9e-325a-472b-b9da-2889e38e2cad/Steel+statistical+yearbook+2009.pdf (visited on 2017-06-15).

[47] World Steel Association. *Steel Statistical Yearbook 2016.* URL: https://www.worldsteel.org/en/dam/jcr:37ad1117-fefc-4df3-b84f-6295478ae460/Steel+Statistical+Yearbook+2016.pdf (visited on 2017-06-15).

[48] Ministry of Chemicals and Fertilizers. *Chemicals And Petrochemicals Statistics At A Glance: 2010.* 2010. URL: http://www.chemicals.gov.in/sites/default/files/Part1_Part2.pdf (visited on 2017-06-15).

[49] Ministry of Chemicals and Fertilizers. *Chemicals And Petrochemicals Statistics At A Glance: 2015.* 2015. URL: http://www.chemicals.gov.in/sites/default/files/Chemicals%20and%20Petrochemicals%20Statistics%20at%20a%20Glance%202015%2812.5.16%29_1.pdf (visited on 2017-06-15).

[50] U.S. Geological Survey. *Mineral Commodity Summaries (1996, 1998-2017).* URL: https://minerals.usgs.gov/minerals/pubs/mcs/ (visited on 2017-06-15).

[51] World Bank. *World Development Indicators*. 2017. URL: http://databank.worldbank.org/data/download/WDI_excel.zip (visited on 2017-09-09).

[52] Central Statistics Office (India). *GDP of India and major Sectors of Economy*. URL: https://data.gov.in/sites/default/files/datafile/GDP_and_Major_Industrial_Sectors_of_Economy_Dataset.xls (visited on 2017-09-30).

[53] Ministry of Road Transport and Highways (India). *Freight and Passenger Movement by Road Transport and Railways during 1950-51 to 2006-07*. URL: https://data.gov.in/node/100696/download (visited on 2017-07-25).

[54] Ministry of Road Transport and Highways (India). *Freight and Passenger Movement by Road Transport and Railways during 1999-2000 to 2011-12*. URL: https://data.gov.in/node/88106/download (visited on 2017-07-25).

[55] Ministry of Railways (India). *Indian Railways: Key Statistics (1970-01 to 2012-13)*. URL: http://www.indianrailways.gov.in/railwayboard/uploads/directorate/stat_econ/downloads/Data_Bank.pdf (visited on 2017-11-27).

[56] Ministry of Railways (India). *Indian Railways Year Book 2015-16*. URL: http://www.indianrailways.gov.in/railwayboard/view_section.jsp?lang=0&id=0,1,304,366,554,1817,1819 (visited on 2017-07-26).

[57] International Association of Public Transport (India). *Metro System in India - Fare Comparison*. URL: http://www.india.uitp.org/articles/metro-system-in-india-fare-comparison (visited on 2017-07-26).

[58] Delhi Metro Rail Cooperation Ltd. *Leaders in Green and Clean Rapid Transit Systems in India*. 2015. URL: http://www.delhimetrorail.com/otherdocuments/cop21.pdf (visited on 2017-07-26).

[59] Directorate General of Civil Aviation (India). *Air Transport Statistics for the Year (2000-01, 2010-11, 2015-16)*. URL: http://dgca.nic.in/reports/stat-ind.htm (visited on 2017-07-26).

[60] RITES Ltd. *Total Transport System Study on Traffic Flows and Modal Costs (Chapter 3)*. 2010. URL: http://planningcommission.gov.in/reports/genrep/trans/Chapter_3.pdf (visited on 2017-11-27).

[61] Nandi Moksnes et al. *2015 OSeMOSYS User Manual*. Tech. rep. 2015. URL: http://www.osemosys.org/uploads/1/8/5/0/18504136/osemosys_manual_-_working_with_text_files_-_2015-11-05.pdf (visited on 2017-04-20).

[62] Andreas Schäfer. *Introducing Behavioral Change in Transportation into Energy/Economy/Environment Models*. Policy Research Working Paper 6234. World Bank, 2012. URL: https://openknowledge.worldbank.org/bitstream/handle/10986/12085/wps6234.pdf?sequence=1&isAllowed=y (visited on 2017-11-27).

[63] Hannah E. Daly et al. *Incorporating travel behaviour and travel time into TIMES energy system models*. In: *Applied Energy* 135 (Dec. 2014), pp. 429–439. ISSN: 0306-2619. DOI: 10.1016/j.apenergy.2014.08.051. URL: http://www.sciencedirect.com/science/article/pii/S0306261914008629 (visited on 2017-06-21).

[64] Paul E. Dodds and Will McDowall. *Methodologies for representing the road transport sector in energy system models*. In: *International Journal of Hydrogen Energy* 39.5 (Feb. 2014), pp. 2345–2358. ISSN: 0360-3199. DOI: 10.1016/j.ijhydene.2013.11.021. URL: http://www.sciencedirect.com/science/article/pii/S0360319913027468 (visited on 2017-05-23).

[65] AEA. *A review of the efficiency and cost assumptions for road transport vehicles to 2050.* Tech. rep. AEA/R/ED57444. 2012. URL: https://www.theccc.org.uk/archive/aws/ED57444%20-%20CCC%20RoadV%20Cost-Eff%20to%202050%20FINAL%2025Apr12.pdf (visited on 2017-11-22).

[66] OECD. *Price level indices.* URL: https://data.oecd.org/price/price-level-indices.htm (visited on 2017-09-01).

[67] Randy Chugh, Maureen Cropper, and Urvashi Narain. *The cost of fuel economy in the Indian passenger vehicle market.* In: *Energy Policy.* Asian Energy Security 39.11 (Nov. 2011), pp. 7174–7183. ISSN: 0301-4215. DOI: 10.1016/j.enpol.2011.08.037. URL: http://www.sciencedirect.com/science/article/pii/S0301421511006343 (visited on 2017-07-19).

[68] Narayan V. Iyer. *A Technical Assessment of Emissions and Fuel Consumption Reduction Potential from Two and Three Wheelers in India.* 2012. URL: http://www.theicct.org/sites/default/files/publications/Iyer_two-three-wheelers_India_August2012.pdf (visited on 2017-11-27).

[69] The Internation Council on Clean Transportation. *Light-commercial vehicles in India, 2014-15.* 2016. URL: http://www.theicct.org/sites/default/files/publications/India%20LCVs_White-Paper_ICCT_23122016.pdf (visited on 2017-11-27).

[70] Global Fuel Economy Initiative. *Estimating the fuel efficiency technology potential of heavy-duty trucks in major markets around the world.* 2016. URL: https://www.globalfueleconomy.org/media/404893/gfei-wp14.pdf (visited on 2017-11-27).

[71] Salil Arora, Anant Vyas, and Larry R. Johnson. *Projections of highway vehicle population, energy demand, and CO2 emissions in India to 2040.* en. In: *Natural Resources Forum* 35.1 (Feb. 2011), pp. 49–62. ISSN: 1477-8947. DOI: 10.1111/j.1477-8947.2011.01341.x. URL: http://onlinelibrary.wiley.com/doi/10.1111/j.1477-8947.2011.01341.x/abstract (visited on 2017-07-19).

[72] McKinsey. *A portfolio of power-trains for Europe a fact-based analysis.* 2010. URL: http://www.fch.europa.eu/sites/default/files/documents/Power_trains_for_Europe.pdf (visited on 2017-06-21).

[73] Ministry of Petroleum And Natural Gas (India). *Tapi Gas Pipeline.* 2014. URL: http://www.pib.nic.in/newsite/mbErel.aspx?relid=113347 (visited on 2017-11-22).

[74] S. N. Naik et al. *Production of first and second generation biofuels: A comprehensive review.* In: *Renewable and Sustainable Energy Reviews* 14.2 (Feb. 2010), pp. 578–597. ISSN: 1364-0321. DOI: 10.1016/j.rser.2009.10.003. URL: http://www.sciencedirect.com/science/article/pii/S1364032109002342 (visited on 2017-10-08).

[75] U.S. Department of Agriculture. *India Biofuels Annual 2016.* GAIN report IN6088. 2016. URL: http://gain.fas.usda.gov/Recent%20GAIN%20Publications/Biofuels%20Annual_New%20Delhi_India_6-24-2016.pdf (visited on 2017-09-13).

[76] Paul E. Dodds and Will McDowall. *A review of hydrogen production technologies for energy system models.* UKSHEC working paper 6. 2012. URL: http://www.wholesem.ac.uk/bartlett/energy/research/themes/energy-systems/hydrogen/WP6_Dodds_Production.pdf (visited on 2017-07-11).

[77] Timor Gül. *An Energy-Economic Scenario Analysis of Alternative Fuels for Transport.* Doctoral Thesis. ETH Zürich, 2008. URL: https://www.psi.ch/eem/PublicationsTabelle/dis2008_guel.pdf (visited on 2017-11-27).

[78] Ministry of Petroleum and Natural Gas (India). *Data for Crude and Products*. 2017. URL: http://ppac.org.in/content/212_1_ImportExport.aspx (visited on 2017-09-13).

[79] World Bank. *World Bank Commodities Price Forecast*. 2017. URL: http://pubdocs.worldbank.org/en/662641493046964412/CMO-April-2017-Forecasts.pdf (visited on 2017-09-07).

[80] OECD/FAO. *Biofuel prices to trend upward*. 2017. URL: http://www.oecd-ilibrary.org/biofuel-prices-to-trend-upward_5jft40h488kf.xlsx?contentType=%2fns%2fTable%2c%2fns%2fGraph%2c%2fns%2fStatisticalPublication&itemId=%2fcontent%2fgraph%2fagr_outlook-2017-graph112-en&mimeType=application%2fvnd.openxmlformats-officedocument.spreadsheetml.sheet&containerItemId=%2fcontent%2fgraph%2fagr_outlook-2017-graph112-en&accessItemIds=%2fcontent%2fbook%2fagr_outlook-2017-en (visited on 2017-09-08).

[81] U.S. Energy Information Administration. *Performance Profiles of Major Energy Producers 2009*. 2011. URL: https://www.eia.gov/finance/performanceprofiles/pdf/020609.pdf (visited on 2017-11-27).

[82] Iain Staffell. *The Energy and Fuel Data Sheet*. 2011. URL: http://www.claverton-energy.com/wordpress/wp-content/uploads/2012/08/the_energy_and_fuel_data_sheet1.pdf (visited on 2017-09-13).

[83] Central Electricity Authority (India). *CO2 Baseline Database for the Indian Power Sector*. 2016. URL: http://www.cea.nic.in/reports/others/thermal/tpece/cdm_co2/user_guide_ver11.pdf (visited on 2017-11-27).

[84] IEA ETSAP. *Oil Refineries*. Technology Brief. 2014. URL: http://www.iea-etsap.org/E-TechDS/PDF/P04_Oil%20Ref_KV_Apr2014_GSOK.pdf (visited on 2017-11-27).

[85] IEA. *IEA Refinery Margins Methodological Notes*. Tech. rep. 2012. URL: https://www.iea.org/media/omrreports/Refining_Margin_Supplement_OMRAUG_12SEP2012.pdf (visited on 2017-11-27).

[86] IHS Global Inc. *Oil and Gas Upstream Cost Study*. Tech. rep. 2015. URL: https://www.eia.gov/analysis/studies/drilling/pdf/upstream.pdf (visited on 2017-09-10).

[87] Suresh Mathur. *Challenges of LNG & Economics of its Use*. 2015. URL: http://www.fipi.org.in/attachments/30Apr-02May15/Suresh%20Mathur.pdf (visited on 2017-09-10).

[88] The Energy and Resources Institute. *Biofuel Promotion in India for Transport: Exploring the Grey Areas*. Policy Brief. 2015. URL: http://www.teriin.org/policybrief/docs/biofuel.pdf (visited on 2017-11-27).

[89] Climate Policy Initative. *Reaching India's Renewable Energy Targets Cost-Effectively*. 2015. URL: https://climatepolicyinitiative.org/wp-content/uploads/2015/04/Reaching-Indias-Renewable-Energy-Targets-Cost-Effectively.pdf (visited on 2017-09-13).

[90] Paul E. Dodds and Will McDowall. *A review of hydrogen delivery technologies for energy system models*. UKSHEC working paper 7. 2012. URL: http://www.wholesem.ac.uk/bartlett/energy/research/themes/energy-systems/hydrogen/WP7_Dodds_Delivery.pdf (visited on 2017-07-07).

[91] Enver Doruk Özdemir. *The future role of alternative powertrains and fuels in the German transport sector: a model based scenario analysis with respect to technical, economic and environmental aspects with a focus on road transport.* Doctoral Thesis. Universität Stuttgart, 2012. URL: http://elib.uni-stuttgart.de/handle/11682/1993 (visited on 2017-06-30).

[92] Brian C. O'Neill et al. *The roads ahead: Narratives for shared socioeconomic pathways describing world futures in the 21st century.* In: *Global Environmental Change* 42.Supplement C (Jan. 2017), pp. 169–180. ISSN: 0959-3780. DOI: 10.1016/j.gloenvcha.2015.01.004. URL: http://www.sciencedirect.com/science/article/pii/S0959378015000060 (visited on 2017-09-17).

[93] Brian C. O'Neill et al. *A new scenario framework for climate change research: the concept of shared socioeconomic pathways.* en. In: *Climatic Change* 122.3 (Feb. 2014), pp. 387–400. ISSN: 0165-0009, 1573-1480. DOI: 10.1007/s10584-013-0905-2. URL: https://link.springer.com/article/10.1007/s10584-013-0905-2 (visited on 2017-05-12).

[94] Keywan Riahi et al. *The Shared Socioeconomic Pathways and their energy, land use, and greenhouse gas emissions implications: An overview.* In: *Global Environmental Change* 42 (Jan. 2017), pp. 153–168. ISSN: 0959-3780. DOI: 10.1016/j.gloenvcha.2016.05.009. URL: http://www.sciencedirect.com/science/article/pii/S0959378016300681 (visited on 2017-04-24).

[95] Samir Kc and Wolfgang Lutz. *The human core of the shared socioeconomic pathways: Population scenarios by age, sex and level of education for all countries to 2100.* In: *Global Environmental Change* 42.Supplement C (Jan. 2017), pp. 181–192. ISSN: 0959-3780. DOI: 10.1016/j.gloenvcha.2014.06.004. URL: http://www.sciencedirect.com/science/article/pii/S0959378014001095 (visited on 2017-10-13).

[96] Leiwen Jiang and Brian C. O'Neill. *Global urbanization projections for the Shared Socioeconomic Pathways.* In: *Global Environmental Change* 42 (Jan. 2017), pp. 193–199. ISSN: 0959-3780. DOI: 10.1016/j.gloenvcha.2015.03.008. URL: http://www.sciencedirect.com/science/article/pii/S0959378015000394 (visited on 2017-10-13).

[97] Jesús Crespo Cuaresma. *Income projections for climate change research: A framework based on human capital dynamics.* In: *Global Environmental Change* 42 (Jan. 2017), pp. 226–236. ISSN: 0959-3780. DOI: 10.1016/j.gloenvcha.2015.02.012. URL: http://www.sciencedirect.com/science/article/pii/S0959378015000382 (visited on 2017-05-05).

[98] Rob Dellink et al. *Long-term economic growth projections in the Shared Socioeconomic Pathways.* In: *Global Environmental Change* 42 (Jan. 2017), pp. 200–214. ISSN: 0959-3780. DOI: 10.1016/j.gloenvcha.2015.06.004. URL: http://www.sciencedirect.com/science/article/pii/S0959378015000837 (visited on 2017-05-05).

[99] Marian Leimbach et al. *Future growth patterns of world regions – A GDP scenario approach.* In: *Global Environmental Change* 42.Supplement C (Jan. 2017), pp. 215–225. ISSN: 0959-3780. DOI: 10.1016/j.gloenvcha.2015.02.005. URL: http://www.sciencedirect.com/science/article/pii/S0959378015000242 (visited on 2017-10-13).

[100] Leiwen Jiang and Brian C. O'Neill. *Household projections for rural and urban areas of major regions of the world.* In: (2009). URL: http://pure.iiasa.ac.at/9123 (visited on 2017-05-08).

[101] Ministry of Home Affairs (India). *Census of India 1971-2011*. URL: http://www.censusindia.gov.in/ (visited on 2017-05-08).

[102] National Sample Survey Office (India). *Energy Sources of Indian Households for Cooking and Lighting, 2011-12*. 2015. URL: http://mospi.nic.in/sites/default/files/publication_reports/nss_report_567.pdf (visited on 2017-11-27).

[103] Tommi Ekholm et al. *Determinants of household energy consumption in India*. In: *Energy Policy*. The socio-economic transition towards a hydrogen economy - findings from European research, with regular papers 38.10 (Oct. 2010), pp. 5696–5707. ISSN: 0301-4215. DOI: 10.1016/j.enpol.2010.05.017. URL: http://www.sciencedirect.com/science/article/pii/S0301421510003885 (visited on 2017-05-17).

[104] Sadhan Mahapatra, H. N. Chanakya, and S. Dasappa. *Evaluation of various energy devices for domestic lighting in India: Technology, economics and CO2 emissions*. In: *Energy for Sustainable Development* 13.4 (Dec. 2009), pp. 271–279. ISSN: 0973-0826. DOI: 10.1016/j.esd.2009.10.005. URL: http://www.sciencedirect.com/science/article/pii/S097308260900074X (visited on 2017-05-31).

[105] Christopher D. Porter et al. *Effects of the Built Environment on Transportation: Energy Use, Greenhouse Gas Emissions, and Other Factors*. In: *Transportation Energy Futures Series* (Mar. 2013). URL: https://trid.trb.org/view.aspx?id=1251624 (visited on 2017-10-21).

[106] Paul L. Lucas et al. *Implications of the international reduction pledges on long-term energy system changes and costs in China and India*. In: *Energy Policy* 63.Supplement C (Dec. 2013), pp. 1032–1041. ISSN: 0301-4215. DOI: 10.1016/j.enpol.2013.09.026. URL: http://www.sciencedirect.com/science/article/pii/S0301421513009506 (visited on 2017-10-04).

# A Appendix

## A.1 General Notes on Data Processing and Representation

All data sets and respective explanations can be found on the attached compact disc. Two major points are to be shortly discussed here:

- For the entire thesis work, calendar years and the closest Indian fiscal year, e.g., calendar year 2014 and fiscal year 2014-15, are used interchangeable. For readability and consistency with some data sources, they are generally referred to by the respective calendar year, e.g., 2014. Only the OSeMOSYS model data file, in line with parallel modeling efforts, uses the ending calendar year of the fiscal year, e.g., 2015 for fiscal year 2014-15, to refer to the respective year.
- Data given for other currencies or base years are converted using the conversion factors as derived in the transport model data sheet. Here, respective values are generally first converted to Indian Rupees, adjusted to the base year using the Indian consumer price index and finally converted to US dollars. For international quantities, e.g., import prices, and partly conversions for intermediate calculations, e.g., vehicle capital cost estimates, a different approach is used based on US or the respective countries' consumer price indices.

## A.2 Compact Disc Content

Following material can be found on the attached compact disc:

- The digital version of the thesis
- Model files incl. input data and results
- The slide set of the final presentation