newTRENDs

Pathways for New Societal Trends and gap analysis for demand models

Deliverable D3.1

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Executive Summary

To achieve the Paris Agreement goals, all countries need to implement two central strategies: i) enhancing energy efficiency (EE) and (ii) decarbonizing the remaining energy supply and demand. Scenarios with different focusses and assumptions have been developed to map this development until 2050. In this context, the newTRENDs project develops the analytical basis for a "2050 Energy Efficiency Vision" by taking into account New Societal Trends in energy demand modeling.

- First, in WP2, we identify the new societal trends and their clusters that are expected to be most relevant or disruptive for the future energy demand. The identification is done based on a wide scanning of existing studies and a series of expert workshops. In the end, 14 major trend clusters are identified. Furthermore, for each cluster, we also develop the narrative to describe the potential mechanisms of its controversial impact and disruptiveness for future energy demand.
- Second, in WP3, we take a closer sectoral perspective to review the impact of the new societal trends on energy demand. Four sectors are considered, including industry, transport, tertiary and residential sectors. Then, to quantitatively analyze their impact, we also identify the gaps for modeling the new trends in the models that are involved in the project.
- Third, in WP5-7, we concretely improve and enhance the energy demand models to integrate the new trends. Based on the updated models, we evaluate the impact of the trends on the energy demand in each sector. This is closely related to the policy questions identified in WP4. Furthermore, back in WP3, we also analyze the macro-economic impacts of the trends.

In this D3.1 report for WP3 of the newTRENDs procject we are focussing on the second step introduced above. It includes six chapters.

This deliverable D3.1 has the following **two objectives**:

1. <u>to analyze and describe by sector and on the macro level how the identified trend clusters might impact the energy demand in the various sectors;</u>
2. <u>to provide an assessment of how the current models are able to model the impact of these trends and provide a qualitative gap analysis of the parts in which the models are not yet well suited to model the new societal trends.</u>

This objective is introduced in chapter 1, together with a description how this deliverable is embedded in the wider WP3.

To quantitatively analyze the impact of new trends, four scenarios are developed:

1. <u>Reference Scenario</u>: the energy demand in each sector will be calculated based on the most recent EU PRIMES reference scenario. Carbon neutrality in 2050 will not be reached.
2. <u>Decarbonization Scenario</u>: we introduce necessary decarbonization policies and measures to reach the carbon neutrality target in 2050.

3. New Societal Trends Scenario: we model how the energy demand will unfold with these trends, when no decarbonization measures are introduced. Carbon neutrality will not be reached in 2050.
4. Decarbonization and New Societal Trends Scenario: we combine how the energy demand develops with the decarbonization measures in place and the unfolding of the new trends. Additionally, policies which influcence the trends in particular might be introduced in the sectoral models. The target of this scenario is carbon neutrality in 2050.

Chapter 2 reviews 15 trend clusters that are identifed to be most relevant for energy demand in WP2. The clusters are further categorized into four groups: "universal", "nice to have", "optional", and "parking lot", assessing their impact on energy demand as well as their relevance to the models in this project. Chapter 3 discusses the impact of these trend clusters in each sector, including industry, transport, tertiary, and residential sectors.

Based on the detailed sectoral review, Chapter 4 introduces the models that are involved in newTRENDs and identifies the modeling gaps in the models. These models are FORECAST-Industry, PRIMES-TREMOVE, FORECAST-Tertiary, FORECAST-Appliance, INVERT, and PRIMES-BuiMo. The authors also summarize the plan for model improvement. Furthermore, since new trends (such as urbanisation, remote work, etc.) might also lead to demand shifts between sectors, we assess such potential linkages from an inter-sectoral perspective. To evaluate the macro-economic impact, Chapter 5 focuses on the general equilibrium modeling based on the GEM-E3 framework. Relevant modeling gaps for the new societal trends are identified and the improvement plans are summarized. At last, we conclude in Chapter 6.

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1. OBJECTIVE

In this Horizon 2020 project newTRENDs, we will analyze the impact of "New Societal Trends" on energy demand and their implications on the long-term carbon neutrality target. These trends encompass both technological and non-technological changes. Examples of these trends include digitalization, sharing economy, prosumaging and circular economy (Brugger et al. 2021).

Based on the New Societal Trends and their clusters identified in WP2, the purpose of WP3 is to model their pathways quantitatively, to analyze their impact on the energy demand in each sector, and to evaluate their implications on the macro economy.

This deliverable has the following two objectives:

1. to analyze and describe by sector how the identified trend clusters might impact the energy demand in the various sectors;
2. to provide an assessment of how the current models are able to model the impact of these trends and provide a qualitative gap analysis of the parts in which the models are not yet well suited to model the new societal trends.

This work is the foundation for the model enhancements in the focus studies (WP5-7) as well as for the scenario runs with the enhanced models.

Four scenarios are defined as shown in Table 1 to assess the impact of the new societal trend on energy demand.

Table 1: Scenarios for analyzing the impacts of new societal trends

Decarbonization Measures Implemented	*Decarbonization Scenario* • Decarbonization measures are implemented for carbon neutrality. • No new societal trends are considered.	*Decarbonization and New Societal Trends Scenario* • Decarbonization measures are implemented for carbon neutrality. • New societal trends are considered and their impacts are evaluated.

Decarbonization Measures Not Implemented	*Reference Scenario* • Based on the latest runs of reference scenario with PRIMES. • No new societal trends are considered.	*New Societal Trends Scenario* • New societal trends are considered and their impacts are evaluated. They can lead to increase or decrease in energy demand.
	New Societal Trends Not Considered	**New Societal Trends Considered**

On the left-hand side, we define two relatively classical scenarios. In the Reference Scenario, the energy demand in each sector will be calculated based on the most recent EU PRIMES reference scenario. In the Decarbonization Scenario, we introduce necessary decarbonization policies and measures to reach the carbon neutrality target in 2050.

On the right-hand side, we define two scenarios in which the New Societal Trends are considered. In the New Societal Trends Scenario, we model how the energy demand will unfold with these trends, when no decarbonization measures are introduced. At last, under the Decarbonization and New Societal Trends Scenario, we combine how the energy demand develops with the decarbonization measures in place and the unfolding of the new trends. Additionally, policies which influcence the trends in particular might be introduced in the sectoral models. While the Decarbonization Scenario and the Decarbonization and New Societal Trends Scenario are target scenarios, which are designed to reach climate neutrality in 2050, the New Societal Trends Scenario will not be able to reach this target. Its purpose lies in identifying the effects that new societal trends might have on future energy demand if now corresponding decarbonization measures are taken.

For a comprehensive analysis of the New Societal Trends under the four scenarios, in WP3, each modelling team will go through four steps as follows:

1. Analyze the trends and their clusters in the context of each sector.
2. Identify the mechanisms and indicators needed to model these trends and summarize the gaps in the current models, including:
    - **Industry**: FORECAST-Industry
    - **Transport**: PRIMES-TREMOVE
    - **Tertiary**: FORECAST-Tertiary
    - **Residential**: FORECAST-Appliance, INVERT, and PRIMES-BuiMo
    - **General equilibrium**: GEM-E3
3. Improve the models in the focus study work packages (WP5, WP6 and WP7).
4. Run the improved models for the four scenarios, analyze the impact of the New Society Trends on the energy demand in each sector, and evaluate their implications on the macro economy.

This report documents the first and second steps listed above (Task 3.1 and 3.2). The remainder of the report is structured as follows:

First, in Chapter 2, we provide a brief summary of the trend clusters identified in WP2. Then in Chapter 3, in a more detailed manner, we discuss how the trends can influence the energy demand in different sectors, including a cross-sectoral perspective. Third, Chapter 4 introduces the models used in this project, identifies the gaps for analyzing new societal trends in their current versions, and introduces how we plan to improve the models in the following work packages. Chapter 5 introduces the General Equilibrium Model GEM-E3 and describes how the trends are affecting this macro-economic modeling. At last, we conclude in Chapter 6.

2. NEW TRENDS AND THEIR CLUSTERS

To identify the most relevant societal trends for energy demand, WP2 of the project started with over 240 trends gathered from previous foresight studies. Then, through three workshops, the partners as well as external stakeholders closely assessed the impact of these trends on the energy demand, selected the most relevant ones, and clustered them into the following 15 trend clusters.

Table 2: Summary of trend clusters from WP2

Relevance	No.	Trend Cluster
Universal	1	Digitalization
	2	Sustainable Cities
	3	Green Transition
	4	Decentralized Work
	5	From Owning to Sharing
	6	Climate Change and Behavior
	7	Circular Economy
Nice to have	8	Socio-Economic Dynamics (Toward Energy Equality)
	9	Water Issues
	10	Green Finance
	11	Demographic Change
Optional	12	Geopolitics/Global Forces
	13	Great Depression II
	14	New Labor
Parking lot	15	Evolving Democratic System

As shown in Table 2, the 15 trend clusters are further categorized into 4 groups, "universal", "nice to have", "optional" and "parking lot", reflecting on one hand their potential impact on future energy demand, and on the other hand their relevance in the modeling activities within this project. Additionally, the D2.1 report of WP2 also developed narratives for these trend clusters, which are briefly summarized as follows.

Concepts and narratives of trend clusters in brief:

1. Digitalization: This cluster summarizes all kinds of trends, which are related to digitalization. On one hand, including the rise of digital data storage and traffic and its corresponding increase in energy consumption of data centers and networks as well as the increase in digital hardware

production. On the other hand, it includes changes in the sectoral energy demand through digitalization (e.g. in the transport sector through the trend of increasing virtual work or in the industrial sector through industry 4.0).

2. Sustainable Cities: This cluster gathers the trends focusing on overcoming future challenges of urban living spaces. Following topics are relevant: food and water supply, transportation, land use, etc.
3. Green Transition: The EU's green transition requires intense initial energy requirements to build new systems, infrastructure and capacities. Rebound effects of these efforts should be monitored and necessary policies and financial instruments should be considered.
4. Decentralized Work: Decentralized work affects energy demand in transportation systems and domestic lives. If people work from home and move outside of city centers, their commute time will increase but the frequency of work-related travel will decrease.
5. From Owning to Sharing: This trend cluster encompasses multiple fields, ranging from cars and equipment, to publications, to living spaces. In summary, it changes the energy demand in material extraction, production, and transportation.
6. Climate Change and Behavior: The activities and behaviors of individuals play an important role in shaping future energy demand. These behaviors can be shaped by national policy and regional governance, including extraction, production, transport, domestic use, etc.
7. Circular Economy: The transition to a circular economy implies numerous systemic changes to socio-economic structures and industrial operations and processes. Previous analyses have shown that today's available technologies with a reasonable economic performance are not sufficient for deep decarbonization in the industry sector. Therefore, turning the EU economy and in particular the production and consumption of CO2-intensive materials into a material-efficient circular economy could substantially contribute to a CO2-neutral economy. In addition, associated effects on energy consumption have not yet been sufficiently analyzed.
8. Socio-Economic Dynamics (Toward Energy Equality): The Covid-19 pandemic highlighted the varying capabilities of healthcare systems across the EU. Deep inequalities like this can redirect investment and development, which implies short-term increases in energy demand for infrastructure, operational capacities, and additional services. While in the long-term, addressing some of these inequalities may eventually lower energy demand - through supporting the healthy and energy-efficient lifestyle of people.
9. Water Issues: Water is linked to every aspect of human living. Its integrated nature across so many human systems amplifies the effects of disruptions. When a region or nation experiences a significant shift in water availability, more energy will be needed to extract and transport water. Additionally, water scarcity can also directly and indirectly create large numbers of refugees and migrants, which further affects the energy demand.

10. Green Finance: Green finance can drive among others the efficiency improvement and electrification process, and at the same time, it can trigger the behavioral change of actors in the private sector and individuals.
11. Demographic Change: In the regions where there is a "youth bulge", the energy consumption is expected to increase, or shift to other regions with moving population. While in the aging regions, the energy demand will also change depending on the energy intensity of the activities that older population engage in and their overall physical health.
12. Geopolitics/Global Forces: The increase in the global population and in the middle class in BRICS states is expected to increase the energy demand. Potential economic growth in Africa also has similar impact. Increasing inequalities will also affect the future energy demand. Besides, the relations between Global North and South and the technological confrontation of US and China can also, to some extent, shift the energy demand between sectors or regions.
13. Great Depression II: Depending on the impacts of the depression on the global economy, there may be a decrease in total energy demand. However, in the longer-term, energy demand may increase as national and regional entities attempt to restart economies with inefficient experiments and large infrastructure build outs.
14. New Labor: Trends in this cluster mainly concern the necessity of new working competencies. Impacts on energy demand in this cluster are also related to the trend cluster digitalization and decentralized work. It also includes trends on the macro level, such as job and markets loss, changing unemployment rates or skilled labor shortage. Relevant impact on energy demand also depends on new political agendas.
15. Evolving Democratic System: Changes in regulatory power and evolving democratic systems might lead to changing energy demands in the respective countries and regions. At the same time, the rise of right-wing populism and nationalism may affect energy demand.

As introduced above, these 15 trend clusters can influence the energy demand in different sectors, to a certain extent, from micro- to macro-level. In Chapter 3, we will go through these trend clusters again and analyze them from a sectoral perspective, in the industry, transport, tertiary, and residential sector. Based on this sectoral review, we will identify the gaps in the current models to analyze these trends and plan for model enhancements in Chapter 4. We will complement the analysis with Section 4.5, focusing on the interaction among sectors due to these trends.

3. NEW TRENDS AND SECTOR ENERGY DEMAND

As listed in Chapter 2, 15 trend clusters are identified to potentially significantly influence the energy demand. In this chapter, we further identify the trends covered by the clusters and discuss their impacts on the different sectors, including industry, transport, tertiary and residential.

3.1 Industry

3.1.1 Digitalization

Digitalization is a trend cluster that can (1) influence the industrial energy consumption (e.g. as an enabler for flexibility), (2) increase the overall energy efficiency and (3) enable the circular economy in the industrial sector. Digitalization will not be part of the modeling activities in the industry sector but considered via scenario assumptions where possible.

3.1.2 Green Transition

The industrial sector is responsible for about a quarter of the EU's GHG emissions (Fleiter et al. 2019). The majority of these emissions are caused by companies in energy-intensive industries (e.g. iron and steel, basic chemicals, cement), which at the same time are responsible for about nearly three third of industrial energy demand. In terms of end-use, most industrial GHG emissions stem from high-temperature process heat, either in the form of steam or hot water, or from direct firing of various types of furnaces. These two end-uses account for 25% and 50% of total direct GHG emissions, respectively. The high temperatures and specific requirements of industrial furnaces limit the use of renewable energy here to biomass or secondary energy sources. Process-related emissions account for about 20% of total direct emissions. They originate from chemical reactions in the production process and their mitigation is technically difficult or even impossible with the processes currently used. Finally, the provision of space heating is also responsible for 5% of GHG emissions, which is unneglectable when assessing industrial energy demand and CO_2 emissions (Herbst et al. 2018; Hartner et al. 2019).

The goal of long-term GHG neutrality is both a political and a societal consensus, but the sector-specific technology pathways as well as the policy frameworks and instruments that should lead to this are still under discussion. Many decarbonization strategies are currently on the table: e.g. the electrification of process heat, a switch to hydrogen or green gas, the increased use of biomass, the market introduction of low-CO_2 processes, the use of CCS and the recycling of CO_2, an expansion of the circular economy and the efficient use of materials. However, the individual contributions of these measures and their efficiency, economic viability and sustainability are still under discussion as new technologies differ in maturity and distance from the market as well as their dependence on resources and infrastructure. In order to shed more light on the role of the industrial sector in the energy and climate transition, the existing industry module of the FORECAST model is used (Fleiter et al. 2018). FORECAST is a bottom-up energy demand model that depicts the technology structure of industry and maps industrial energy consumption, emissions and costs at the process level (see Section 4.1).

3.1.3 From Owning to Sharing

From owning to sharing is a trend that can (1) influence the industrial energy consumption and CO_2-emissions (e.g. by reducing the demand for new products), and (2) be also part of enabling a low-carbon circular industry sector. From owning to sharing will not be part of the modeling activities for the industry sector but considered via scenario assumptions.

3.1.4 Circular Economy

The concept of Circular Economy (CE) gains momentum in the political debate across all stakeholders, synergies exist between the decarbonization and the CE policy agendas (e.g. Green Deal, Circular Economy Action Plan). Consequently, circular material uses and their connection to the energy system through resource, material, and energy flows have to be taken into account in integrated policymaking, integrated energy-material modeling and the analysis of ambitious GHG mitigation pathways. Moreover, sustainable production plays an essential role in promoting sustainable development, as emphasized by the UN's Sustainable Development Goal (SDG) number 12, since it plays an important role in the way that our societies produce and consume goods and services (Herbst and Zanoni 2020).

Especially, strategies grouped under the umbrella concept of CE are considered promising for the GHG emission reduction while maintaining economic growth (Di Maio et al. 2017; Haas et al. 2015). The industrial sector, and especially the basic industry, is of particular importance since a large share of the GHG emitted can be traced back to these and the mitigation is challenging (European Commission 2018; Hertwich et al. 2020; Shanks et al. 2019).

Scenario analyses that investigate potential impacts of CE on GHG emissions can support decision making e.g. via the assessment of indvidual CE measures or whole sectors. Even though current assessments are modeling the impact of those measures to a certain degree, a more detailed quantitative and consistent investigation of CE impact on industrial energy demand and CO_2-emission modeling, including the analysis of costs and policies is still missing. Especially the modeling of supporting policies has been neglected so far (IEA 2019; Le Den et al. 2020a; Material Economics 2018; Pauliuk et al. 2021; Pauliuk and Heeren 2021).

The main aim for the industrial sector in newTRENDs will be the improvement and enhancements of the existing modeling techniques for industrial energy demand and CO_2 emissions projections to support the impact analysis of a circular low-carbon industry (see Section 4.1 and WP 6).

3.2 Transport

The following provides a brief overview of key new trends which are particularly relevant to the transport sector.

3.2.1 Digitalization

As technology progresses, digitalization becomes fundamental in every aspect of modern life. The transport sector is no exception to this. Digitalization in transport is inherently part of the smart-mobility nexus, including the following trends:

- Flexible transport services started as a door-to-door Dial-a-Ride service already back in the '70s and have transformed today into demand-responsive services that utilize fixed, semi-fixed or dynamic routing based on user demand, developments and applications of Information and Communication Technologies and current state-of-the-art transport telematics (Nelson et al. 2010; Wright et al. 2014).
- Intelligent transport systems and infrastructure are empowered by the progressing technology of information and communications, big data, cloud computing, the internet of things and artificial intelligence, which could improve decision-making by enhancing the ability for regulators, operators, planners, and transportation users to collect, analyze, distribute, and learn from transport data (Butler et al. 2021).
- Autonomous vehicles can decrease emissions, improve fuel economy and safety, reduce driver costs, and offer mobility and inclusion benefits to older people and the less able (Paddeu et al. 2020). Different levels of vehicle automation are currently available in or expected to enter the market in the near future. They are part of the current trend of automation and manufacturing, which is called digitalization Industry 4.0 (Sell et al. 2019).

Although digitalization can facilitate the transition to a greener and more sustainable transport sector, there are risks that could lead to opposite effects. Noussan and Tagliapietra (2020) studied the effects of digitalization on mobility demand and suggest the necessity of proper policy uptake in order to promote an optimized and shared use of alternative transport options, to achieve an efficient and effective way of adoption of the latest technology advancements. This implies that potential rebound effects in increased energy use in transport, simply because of the easier accessibility to the service, will need to be effectively disincentivized.

3.2.2 Sustainable Cities

As part of the climate change mitigation effort, the transport sector is expected to be reshaped with greener and more sustainable options and solutions. Urban transportation is in the midst of a two-fold transformation (Reul et al. 2021): (1) acknowledging and taking actions over climate responsibilities through sustainable transport systems, and (2) incorporating new trends and practices such as shared mobility, autonomous cars and electric vehicles in the cities.

Hence, there is a growing effort to increase the sustainability of the transport systems within the cities, driven by the climate change mitigation but also by the urgency to improve the quality of life of the people in the cities, by reducing air pollution, among others. So, sustainability can be characterized as a standalone trend, i.e. sustainable transport:

- Sustainable Transport: Improvements in quality of life resulting from environmental sustainability in the form of reduced pollution and health benefits have been widely considered in the literature. To this end, sustainability in the transport system itself can have a similar effect (Ogryzek et al. 2020). Using the paradigm of Banister (2008), a sustainable transport system is a result of four principals that local policy makers should focus on: (1) reduction of travel needs by providing different means of substitution; (2) transport policy shift such as re-evaluating the road hierarchy in favor of pedestrian, cyclists, and public transport; (3) distance reduction by decentralization of different services; (4) technological innovation.

To achieve sustainable mobility service in cities through technological innovation, electric and autonomous vehicles are seen as an integral part of future smart cities (Lim and Taeihagh 2018). The deployment of such technologies can lead to environmental benefits such as reduced GHG emissions and pollutants, decreased energy consumption and costs, lower vehicle ownership and better use of the fleet (Boyacı et al. 2015; Fagnant and Kockelman 2014; Acheampong and Siiba 2020; Iacobucci et al. 2018; Greenblatt and Shaheen 2015; Greenblatt and Saxena 2015; Shaheen and Chan 2015; Anderson et al. 2016).

3.2.3 Green Transition

The transport sector is expected to hold a significant role in the green transition of the currently carbon intensive energy systems towards carbon neutrality. In this regard, there are two main trends in the transport sector:

- Electric vehicle in the passenger-travelling sector: The largest emitting sector in transport is that of passenger cars. Numerous studies and scenario analyses (McCollum et al. 2014; Zhang et al. 2018; Zhang and Fujimori 2020; European Commission 2018) identify electric vehicles as the natural choice to reduce emissions in the car segment. These findings are also supported by the progressively decreasing battery costs as well as provisions on the development of electricity recharging infrastructure across the EU countries.

- Fuel switching in the road freight, aviation, and shipping sector: Undoubtedly, strong effort is required also from other transport sectors to contribute to the "greening" of the overall transport by 2030 and by 2050. Road freight, aviation and shipping currently represent the most inflexible to abate emissions sectors. Various scenario outlooks depict the importance of the use of biofuels (produced with sustainable ways) as well as the use of synthetic e-liquids (which are produced from green hydrogen).

The above indicates that there does not exist a single solution to decarbonize the whole transport sector. Over the years, it has become evident, that different transport sub-sectors shall require tailored solutions to enable their decarbonization. This justifies the existence of the aforementioned two trends: one focusing on private road transport and one on long distance road freight, transport, aviation and maritime. In the former case, the high uptake of electric vehicles needs to be accompanied by an equivalent reduction in the upstream emissions related to the generation of electricity. However, the currently limited electricity recharging infrastructure network and the higher electric vehicle purchasing prices, pose barriers for a successful transition towards major uptake of electric vehicles (Zhang et al. 2018; Statharas et al. 2019). Regarding the cost of the batteries, various studies show that technological progress can lead to cost parity between ICE and EV cars already before 2030 (Ouyang et al. 2021; Sioshansi and Webb 2019). On the other hand, to promote the fuel switching in the road freight, aviation and shipping sector, strong policy support is also needed. We acknowledge that the fuel switching may imply a change in the operating costs of the various transport market segments (e.g. a shift conventional ICE to battery electric vehicles will imply lower running costs). Such fuel switches may lead to modal shifts, when one transport mode increases its competitive advantage over another alternative.

3.2.4 Decentralized Work

Another outcome of the quick uptake of digital technologies is the possibility of working from home, or from places other than common workplaces. The outbreak of COVID-19 also enhanced this trend, as the lockdown enforcement acted as a catalyst for a steep increase in people working from home (Boland et al. 2020). In their survey Shibayama et al. (2021) find that people with home office capability, adopted "working from home" in levels between 60 % and 80 %, while when presence at work was essential, the relevant percentage reached 30 %, implying a strong shift to home office practices in general. Although preliminary studies show that passenger transport demand may remain lower than what a counterfactual reality (with no Covid-19 pandemic) would suggest for the near future trends of transport demand, more research is needed in this regard.

Decentralized work is considered to have a strong positive environmental impact. This is primarily derived by the reduction in the travelled distance (van Lier et al. 2014) as teleworkers can reduce their travel to zero on teleworking days. Telecommuting can also alleviate congestion due to travel on non-peak hours when flexible working hours are an available option (Lachapelle et al. 2018). Depending on the replaced means of transport that was used, decentralized work can lead to even further reduction of GHG emissions (van Lier et al. 2014) and pollutants (Han and Hong 2020).

Contrastingly, Cerqueira et al. (2020) and O'Brien and Yazdani Aliabadi (2020) show some skepticism over the environmental benefits of decentralized work, as strong rebound effects may occur. The environmental benefits are highly dependent on contextual details (O'Brien and Yazdani Aliabadi 2020), as studies indicate that negative impacts due to high travel activity in non-peak hours, longer non-work trips, higher average reported travel activity from teleworkers, and additional trips due to living far from work may occur. A proper model-based quantification of the rebound effects presupposes a case-by-case analysis and rich representation of the geographical dimension.

3.2.5 From Owning to Sharing

With the latest technology advancements in the automobile industry, new trends have emerged in the transport sector, introducing ways of more efficient activity and energy management. Sharing economy is becoming more and more popular as a concept, although it comes from way back to collaborative consumption concepts in ‘70s (Felson and Spaeth 1978). Latest research focuses on the effects of mobility as a service, where demand for transport can be met by sharing vehicles, by passing the need for purchasing and owning one. Hence, users of the shared mobility service may rent an available car from wherever it is parked, use it and leave it to the next user within the limits of a specified area (Boyacı et al. 2015).

The advent of new smartphone technologies supports applications that can facilitate vehicle sharing by providing the interface for payments transactions, availability of service and mobility maps, and have led to quicker adoption and evolution of this trend (Gurumurthy and Kockelman 2018; Beojone and Geroliminis 2021; Mathew et al. 2019). Mobility as a service can be further expanded to other alternative means of transport such as bicycles and e-scooters, as well as services and practices such as on-demand ride and ride sharing, providing utility and convenience while saving costs, reducing vehicle usage, vehicle ownership and vehicle driven miles (Shaheen and Chan 2015). Traditional services such as public transport can be integrated with the abovementioned shared economy practices using a single online interface for payment, journey planning and other traveler information (Ho et al. 2018). The adoption of transport shared economy may show significant reductions in car ownership and congestion levels and probably energy efficiency improvements, emission and cost reductions (Boyacı et al. 2015; Fagnant and Kockelman 2014; Acheampong and Siiba 2020; Iacobucci et al. 2018; Greenblatt and Shaheen

2015; Shaheen and Chan 2015). One can expect a strong reduction in vehicle sales and potential job losses in the car manufacturing industry in case car sales start following a decreasing trend as a result of the uptake of sharing economy.

Shared mobility, which can help improve the total transport system efficiency and reduce traffic, can be facilitated with modern smartphone applications, which can provide quickly and easily the interface for payment transactions, availability of service and mobility maps, journey planning and other traveler information (Gurumurthy and Kockelman 2018; Beojone and Geroliminis 2021; Mathew et al. 2019). In the context of a growing digitalization nexus, there can be a strong market with autonomous shared vehicles to further enhance the experience of travelling (Iacobucci et al. 2018). The combination of autonomous vehicle capability and a car sharing system could lead up to 10 % fuel economy improvements (Greenblatt and Shaheen 2015) and become a more cost-efficient choice (Iacobucci et al. 2018; Paddeu et al. 2020); naturally, economic benefits could be substantially higher than a driven car service (e.g., Uber) as no driver salary is needed. Obviously, the use of electrically chargeable shared vehicles would maximise fuel savings and the environmental positive impacts. The outbreak of coronavirus (COVID-19) has cast serious doubts on the sustainability of shared mobility (Shokouhyar et al. 2021; Strulak-Wójcikiewicz and Lemke 2019) due to potential hygiene issues. More evidence is required in this respect to understand how the pandemic has influenced people willing to share a car with strangers.

3.3 Tertiary Sector

As of today, the tertiary sector contributes by approximately 29 % (870TWh in 2018) to final electricity demand and by approximately 20 % to final heating demand in Europe (Eurostat 2020). Given the high share in electricity demand, the accurate representation of demand drivers in energy demand models is of high interest regarding the understanding and development of future electricity demand.

With the FORECAST Tertiary model, we aim to improve the understanding of the demand drivers in the tertiary sector and focus on new societal trends which are likely to impact future electricity demand. Based on the selection of trend clusters in WP2 and the ongoing work from other projects, the following trends were identified, which can be considered as relevant for the tertiary sector, as well as impacting other demand sectors due to close sector-interlinkages. It is emphasized that a trend identification does not necessarily indicate whether energy demand will increase or decrease given such sector-interlinkages as well as the currently open level of efficiency, efficiency improvement potentials and trend uptake in the sector. Such drivers need to be properly quantified to understand the impact of such trends on overall energy demand and especially electricity demand in the future.

From the 15 trend clusters defined in WP2 (see Table 2), digitalization is expected to be one of the main drivers in the future regarding changes in energy demand in the tertiary sector as well as in other demand sectors. However, the term of digitalization needs to be better defined in relation to the energy demand development, as different definitions exist, what digitalization describes. From our viewpoint, current research on digitalization (Tronvoll et al. 2020; Paschou et al. 2020) focuses on the understanding of processes needed to transform manufacturing companies by digitalization into more service-oriented companies (servitization). Other research on different forms of digitalization in demand sectors such as transportation, households or the tertiary sector are also focusing more on process-related aspects such as e.g., the transformation of the supply chain (Cichosz et al. 2020). Therefore, little knowledge is available on how the digitalization-related drivers impact the energy demand. Additionally, other digitalization processes in the service industry also impact the development of the tertiary sector. Within WP2, such processes have been discussed and structured regarding their potential for becoming relevant trends in the future and being selected for building the foundation for the further analysis. The trends in focus were classified as “decentralized work”, “online shopping”, “cloud-based services, big data and 5G” and “from owning to sharing”. In the following, these trends will be described in a qualitative way, to provide a better understanding of the trends’ narrative.

3.3.1 Digitalization

In the tertiary sector, there are two trends under the digitalization cluster that are particularly relevant for the energy demand.

- Online shopping and food delivery: The demand for online shopping and food delivery has also increased strongly due to the Covid impact (Dannenberg et al. 2020). Although it was expected that this trend was going to grow independent of the global crisis, the pace and sector transformation certainly has increased. People buying goods via the internet, change the way goods are processed, stored, presented, and transported. Therefore, it is expected that the demand for shopping areas, restaurants and related building surfaces and demand will decrease whereas the demand for large storage and logistic facilities and transportation options will increase.
- Cloud-based services, big data and 5G: The demand for cloud-based services has also seen an accelerated increase in the past year (Montevecchi et al. 2020). However, already starting from 2014 onwards, large data center providers as well as data companies have been increasing their services. Partially driven by new data protection laws as well as new and/or low-cost services, the demand for cloud storage and cloud services has increased. Additionally, industrial sensors, databased analytics as well as streaming services grew in a rapid pace, adding to the demand of ICT services (data processing and storage). In contrast to this strong demand, electricity demand from the ICT sub-sector grew only moderately, as recent studies highlight (Masanet et al. 2020; Jakob et al. 2021; Müller et al. 2021). This is explained by the fact that ICT services were outsources from small in-house data centers to large data centers

that are usually more energy-efficient.[1] With large potentials for automated processes and e.g. automated driving, large data processing, storage and transmission will be needed in the future, which translates into a strong growth in data center construction (Fasan 2021). Therefore, it is likely that electricity demand from ICT services will increase in the future and this demand increase will be only partially compensated for by increasing efficiency-related processes. Indeed, Moore's law will come to an end (Rotman 2020) and other efficiency potentials (lowering the PUE, increase virtualization) will be saturated.

3.3.2 Green Transition

In the green transition of the tertiary sector, new services might be the drivers for changes, specifically in sub sectors such as financing or hospitality services. Products and services such as crowd financing, sustainable goods and food in retail market might see increasing shares. However, the impact of such green trends is currently ignored, as the understanding of their impact on the energy demand in the services sector remains open. Additionally, **rebound effects** regarding energy demand are likely to occur within many of the new societal green trends. These rebound effects affect tertiary sub-sectors as well as non-tertiary sectors such as residential and transport. At the current level, it remains open to which extent these rebound effects will balance any energy demand-related effects of the green transition.

3.3.3 Decentralized Work

Decentralized work has seen a strong push in the last year due to the global Covid crisis. In many tertiary sub-sectors, working from home was one of the main options to reduce contacts with other persons, to avoid the transfer of the Sars-Cov2 virus. Either implemented due to policies (e.g., Switzerland, Germany, France etc.) or due to company regulations (e.g., in the financial and insurance sector: SwissRe, Zurich, Adecco, Credit Suisse etc.), employees were forced to work from home wherever possible. This led to a strong push towards more digitalized processes and more cloud services for the tertiary sector as well as a short-term demand increase for electronic goods due to additional working infrastructure at home.

Additionally, electricity consumption was shifted from office space to private homes and energy demand for commuting has changed. It is expected that for some services in some sub-sectors the shift towards home office will be

[1] In large and cloud-based data centers (DC) IT services usually are provided more efficiently as the degree of virtualization of servers and storage is more advanced and servers, storage and network devices are power usage effectiveness (PUE = 1) except for micro-SME where the number of servers is so small that no extra cooling and ventilation is needed.

sustainable, at least to some extent, as employees as well as companies do profit from such development by decreasing need for commuting and decreasing demand for costly office space (Milasi et al. 2020; Lund et al. 2020; Samek Lodovici et al. 2021). In our analysis, we will quantify the impact of this trend on overall energy demand in the tertiary sector as well as the interlinkages to other sectors such as residential and transportation.[2]

3.3.4 From Owning to Sharing

Several initiatives in the recent past have emerged, which promote the concept of sharing instead of owning (Kim et al. 2017). Starting with new concepts for the use of goods in the neighborhood (e.g., the Swiss pumpipumpe[3] or Sharely), devices are no longer owned by every individual but rather shared amongst several users. This leads to a reduced number of equipment (Nishino et al. 2017) and reduced investment needs, but increases service and data-related energy demand. In the context of urbanization, it is expected that this trend will continue to grow, shifting energy demand between sub-sectors as well as between sectors.

Besides these main tertiary-sector-related trends, further trends are in focus of the newTRENDs project and included in the analysis of the tertiary sector (e.g., circular economy, healthy ageing, likely new labor, and potential rebound effects). These trends are less pronounced or show a slower uptake rate and, therefore, their impact on energy demand in the tertiary sector is less certain.

3.3.5 Circular Economy

In the context of the newTRENDs project, the impact of the circular economy is assessed in form of LCA (life-cycle assessment) and use of construction materials (Hossain and Ng 2018) in the built environment of the tertiary sector and based on recycled materials in the industry sector. Depending on the scenario, new buildings could be built with recycled materials, biomass-based materials (structure as well as envelope/insulation) or new materials, which are less energy- intensive. Depending on the refurbishment of the tertiary building stock, the market uptake of such materials can increase strongly in the future and reduce the demand for related energy in production.

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2 For some appliances, FORECAST-Appliance also consider their energy consumption in "stand-by mode", including washing machine, drier, dishwasher, television, computer screens, set-top boxes, laptop computers, desktop computers, Vacuum-cleaner (wireless), and coffee machine.

3 Pumpipumpe is a word game for “pumpi” which is a manual air pump, and “pumpe” which means to borrow. The concept foresees that one is putting a sticker on the letter box for each tool one has at home, and a neighbor could borrow instead of buying his own. On an interactive map, a person who is in need for a tool can check for someone in the neighborhood offering such equipment.

Other aspects of the circular economy are already well integrated in the tertiary sector (and in its modeling) in many different areas on smaller or larger scale and, therefore, not considered as new trends. Recycling is already often applied in cases such as the use and re-use of e.g., toner cartridges or the use of recycled paper in the office environment. Also recycling of electronic devices is often organized via the tertiary sector. As the respective energy demand of such services is small and reflected in the current statistics, no changes are included in the modeling framework.

3.3.6 Demographic Change

In the tertiary sector, there are two trends under the demographic change cluster, which can influence the energy demand.

- Population aging and elderly care: In many European countries, it can be observed based on the development of home ownership rates per age class (Andrews and Caldera Sánchez 2011) that elderly people are staying longer at home before they enter nursing- or retirement homes (elderly care). Until such moment, they often rely on mobile services at home such as food delivery, cleaning, or sanitary support, amongst others. Based on the past development, it is expected that this trend will continue in the future. Therefore, the demand for retirement homes and the specific services will change besides changing demand patterns for hospitals, medication, and others. These service changes lead to changes in energy demand for different tertiary sub-sectors. While the focus is on the population aging, also these trends impact the use of buildings used by younger age classes, e.g., schools and universities. However, there are counter-acting effects such as an increasing floor area demand per pupil, which balances the potential demand reduction for primary and secondary schools.
- New labor: Under new labor, we expect the creation of new job profiles, which relate to the described trends. As younger people tend to uptake new trends more rapidly and adjust to new demands accordingly, this trend is grouped under the demographic change. Data analysts, IT-service technicians, support staff to name a few of such professions will see a strong growth, beyond current levels. With these new labor categories, new energy- related demands will emerge, which should be considered in the tertiary sector energy balance.

3.4 Residential Sector

In the following, we provide an overview of key new trends particularly relevant to the residential sector.

3.4.1 Digitalization

Digitalization is a mega trend that can (1) influence the energy consumption, (2) increase the overall energy efficiency and improve the renewable share of heating and cooling demand (Lyons 2019), and (3) enable the demand-side management in the residential sector. Several trends are involved in this cluster and their impact can also spill into the electricity system.

- Diffusion of network connected devices: The electricity consumption by appliances in the residential sector is impacted by the network connected plug-load devices, for example, routers, set-top boxes, smart speakers, computers, telephones, tablets, etc. (IEA 2020). At the same time, this leads to more electricity consumption for data storage (e.g. data centers) and transmission (e.g. wide area network, WAN) in the upstream. At last, the diffusion of smart network connected appliances (e.g. dishwasher, washing machine, dryer, etc.), which can be remotely or even automatically controlled, also improves the demand-side flexibility of the residential sector (Kandler 2017).
- From consumers to prosumagers: With a PV system, a household can sell electricity to the grid in the hours when the generation is higher than the consumption, so the household becomes also a producer apart from a pure consumer, i.e. a "prosumer". Additionally, supported by a home energy management system (HEMS), a household can further reduce its energy cost by optimally managing the operation of its energy system, including smart appliances, space heating (heat pump), space cooling, hot water, electric vehicle (if available), PV, and battery. So, the household becomes a "prosumager" (i.e. consumer + producer + manager). In this way, the self-consumption rate of the PV generation rate can be increased (Kandler 2017). A similar idea also applies to other hybrid heating systems combining different heating appliances: natural gas boilers, solar thermal collectors, heat pumps and resistance heaters (Heinen et al. 2016; Mancarella 2014).

In summary, digitalization on one hand changes the daily life of households with new products, and on the other hand also provides opportunities for energy cost reduction and decarbonization by optimizing operations, planning and business models, and by connecting producers of heat and cold, users, local stakeholders and energy markets (Rothballer 2018; Lyons 2019). Furthermore, for specific households, digitalization can also optimize their energy consumption behavior. This contributes to changes in energy market design and is a driver of smart buildings, smart communities, smart cities, distributed energy and DHC (Lyons 2019).

3.4.2 Sustainable Cities

In 2018, 39.3 % of the population in the EU lived in cities, 31.6% lived in towns and suburbs, and 29.1% lived in rural areas (Eurostat 2020). Making cities sustainable is vital. In this context, the main challenge is to accommodate a greater number of people while reducing the impacts on the environment, which are the main cause for climate change (IPCC 2014).

- Multiple benefits for citizens: Households have a large impact on energy intensity and final energy consumption. Their energy intensity is increasing and at the same time 26.1% of the final energy consumption in the EU 28 was attributed to the sector in 2018 (Eurostat 2020). The potential for energy consumption reduction of households is large and is set as a key priority in the policy goals and directives by the European Commission (Paulou et al. 2014; Saheb et al. 2015; European Commission 2018).Relatedly, the improvement of the quality of life of city residents is a priority. Energy efficiency improvements in this sector do not only contribute to climate and energy targets. Rather, multiple benefits may result in particular from building retrofitting like increasing comfort, improved health conditions of living and improvement of air quality in cities (Shnapp et al. 2020).
- District heating and cooling (DHC) infrastructure: District heating and cooling infrastructure is an important infrastructure, which may facilitate the improvement of overall primary energy efficiency in the heating and cooling sector in particular of urban areas. For this reason, the Energy Efficiency Directive (European Parliament and the Council 2018) has dedicated a separate section to this topic. Thus, the transition to more sustainable cities increasingly might take up the evolution of existing DHC grids towards more efficient, renewable and low-temperature 4th and 5th generation DHC and the investment into new grids where heating or cooling densities are sufficiently high.

3.4.3 Green Transition

The building sector is the world's biggest consumer of final energy and the largest emitter of GHGs (United Nations Environment Programme 2020). The already planned and ongoing green transition of the energy system, at large, requires buildings and households to play an active role. In addition to the supply side-oriented transition, all prominent scenarios for the transformation of the energy system also include the reduction of the demand for current energy services by increasing energy efficiency (Dütschke et al. 2021).

To achieve those overarching goals, two main concepts are discussed here:on one hand, the coupling of electricity to other energy sectors — electrification of heat for residential buildings and, on the other hand, the role of decentralized renewable energy systems, and increased citizen awareness. Local generation systems enable the prosuming behavior of households, increase the RES shares of electricity production and can improve the energy efficiency of the sector. The latter can be realized by the reduction of energy demand through energy renovations demand-response flexibility (especially relating to electric appliances), electrification of energy uses (space heating, cooling, domestic hot water), storage and increased involvement of citizens in the “household energy system”. Energy renovations — and especially deep renovations — at scale have been proven a difficult task to accomplish for various reasons. The effectivness and uptake of cost-effective energy renovations, as the Renovation Wave Communication of the European Commission stresses (European Commission, 2020), is set as the outmost priority for Member States to reduce energy demand. This is to happen through: strengthening information, legal certainty and incentives; ensuring adequate and well-targeted funding; increasing the capacity to prepare and implement projects; promoting comprehensive and integrated renovation interventions, and making the construction ecosystem fit to deliver sustainable renovation (European Commission, 2020).

In this context, the renewable energy prosumers are active energy citizens who may be involved in producing and self-consuming renewable energy. They are potential participants in the energy markets across different sectors (electricity, transport, heating and cooling), to provide services (e.g. aggregation) or energy efficiency support (Campos and Marín-González 2020).

3.4.4 Decentralized Work

Since the beginning of 2020, due to the COVID-19 pandemic, working from home has become the norm in many professions. However, the pandemic cannot be simply seen as a driver for energy transition but rather as a major disruption that could potentially have longer-term impacts on household energy consumption behavior and the environment (Edomah and Ndulue 2020; Zhou and Yang 2016). The study of global macroeconomic impacts of COVID-19 already suggests potential scenarios that indicate significant impacts on households (McKibbin and Fernando 2020).

Cheshmehzangi (2020) concludes that the impacts on household electricity costs associated with heating and cooling will largely depend on potential transitions for work-from-home initiatives and longer indoor stays. However, if we take a look at the buildings sector, we see that the demand has shifted from the services to the residential sector. In reality, the total demand remains constant, with a marginal decrease in industrial demand load (Qarnain et al. 2020).

More detailed analyses of the impact of Covid-19 on residential load profiles are expected to be published in the context of newTRENDs (Task 5.1) and beyond. The trend of work-from-home may also affect the potential for load shifting and prosumaging behavior of related households. Furthermore, the pandemic might be the initiation of potential longer-term shifts of energy demand from office spaces to residential homes and the overall impact on the demand for building space, which go well beyond the pandemic.

3.4.5 Demographic Change

The current world population, of 7.6 billion, is predicted to reach 8.6 billion in 2030 and 9.8 billion in 2050 (UN 2017). Moreover, the urban population, in 2014, accounted for 54 % of the total global population. This signifies a 20 % increase since 1960. By contrast, in the EU the population is forseen to remain stable for the next two decades and then decrease from 2040 onwards, while the effect of immigrational patterns is not clear in the longer term, as it is expected to be affected by emergency measures limiting the mobility of people (European Commission 2020b). In this cluster, two relevant trends are being identified for the residential sector. First, in addition to the need to accommodate more and more people in the urban built environment, the profiles of citizens and the equivalent socio-economic factors are also crucial to be able to increase energy efficiency and the uptake of renewable energy sources in buildings.Second, the population age also has an impact on the investments decisions (technology adoption and building renovation) and behavioral aspects (e.g. target temperature of heating and cooling).

3.4.6 Climate Change and Behavior

The activities and behaviors of citizens are important in shaping future energy demand. Energy demand reduction is considered one of the most important and effective ways to limit the impact of the residential sector on the climate. Citizens' behaviors can be shaped by strong policies that incentivize decisions and actions that reduce household energy demand. These policies can be national, EU or supranational like the Paris Agreement and they can have many forms — from subsidy schemes on specific technologies to awareness campaigns for households.

The above-mentioned policies, that are also shaped by the National Energy and Climate Plans (NECPs) of EU Member States, and policy instruments can be implemented to mitigate or remove the various market and non-market barriers and facilitate energy efficiency investment for the residential sector and, thus, help mitigate climate change. These investments – by households – relate to the building shell, the technical equipment, local energy generation and equipment for sending electricity price signals to consumers, thus allowing the implementation of demand response schemes (Fotiou et al. 2019). Based on this multitude of policy instruments and measures, the awareness, investment decision-making, and the ability to afford energy efficiency measures affects energy demand, final energy consumption, the fuel mix used by the residential sector and, consequently, climate mitigation goals.

3.4.7 Socio-economic Dynamics

Despite the widely recognized benefits of energy efficiency (i.e., in terms of energy savings, cost reduction, job creation, etc.), the large potential of energy efficiency in buildings remains significantly unexploited in the EU Member States. The limited amount of energy efficiency investment, despite being largely cost-effective according to engineering-economic analysis, challenges policy making (Fotiou et al. 2019).

These barriers to energy efficiency investment can be split in market and non-market related ones (Golove and Eto 1996). Market barriers are related to "true" costs (that are actually paid by consumers) and issues related to the access to capital resources, whereas non-market barriers refer to elements which do not have a direct payable or "true" cost and are often termed as "perceived costs" (Valentová 2010).

A crucial barrier for energy efficiency identified (Ameli and Brandt 2015; Golove and Eto 1996; Paiho and Ahvenniemi 2017; Palm and Reindl 2018; Valentová 2010), is the poor access to capital funding. This constitutes a severe barrier for low-income households, as their family budget can only allocate small parts of their income to energy-related expenditures, as well as to elderly homeowners, who might have difficulties getting loans for the investments. Some studies even conclude that energy efficiency investment without subsidies is not viable from an owner's perspective, especially for low-income households (Mikulić et al. 2016). So, for a **just energy transition**, we need to develop policies to minimize the inequalities and overcome barriers stemming from income constraints.

3.4.8 Green Finance

Financing of investments that provide environmental benefits in the broader context of sustainable development but also specific to the buildings sector directly relates to the issues tackled by the research on socio-economic dynamics (see section above).

In its vision "A Clean Planet for all" the European Commission provides a "strategic long-term vision for a prosperous, modern, competitive and climate neutral economy" (European Commission 2018). Therein, the commission indicates the need for more intensified actions to substantially improve the energy performances of buildings, highlighting the need to remove the market barriers for buildings renovation. Despite various policies implemented to address some of these barriers, current investments in buildings remain at suboptimal levels. Overall, due to financing instruments involving different stakeholders and due to the complex nature of the sector, there is no single solution to accelerate energy renovation investment in buildings (Bertoldi et al. 2021).

Market barriers include hidden up-front investment costs (Golove and Eto 1996), as well as the difficulty of households to access capital funding (i.e., high interest rates for loans). Hidden up-front investment costs are not directly related to material or labor costs for renovation, but are nonetheless true payable costs (Fotiou et al. 2019). With the development of green finance, these problems will be improved to a certain extent. One crucial instrument to improve green financing is the EU Taxonomy, established by means of Regulation (EU) 2020/852 (European Commission 2020a).It sets out the framework for assessing the environmental impact of economic activities. Economic activities that are counted under the EU Taxonomy need on one hand to substantially contribute to at least one of six environmental targets and on the other hand "do no harm" in all other dimensions.[4] As a result, except for specific green finance solutions, the wider reaching EU sustainable taxonomy will affect the decarbonization and financing of solutions for the residential sector.

3.4.9 Great Depression II

Reduced disposable income hinders investments by households in energy efficiency measures, thus reducing the potential for achieving energy savings. Not only does this affect the ability of citizens to invest in energy renovation but also to cover their current fuel purchasing expenses. If no corresponding measures are taken, a great depression might lead to a strong increase of economic inequality and reduce households' available budget for energy-related expenses, especially for the investment of efficiency measures. Measures for recovery can help to dampen the negative effects, nevertheless the longer-term outlook remains uncertain, considering both the public health and the economic risks.

Additionally, together with demographic changes, green finance and the socio-economic dynamics, this trend shapes the non-technical aspects and constraints the transition of households from consumers to prosumagers.

4 For more and current details, see the European Commission's website on the EU taxonomy: EU taxonomy for sustainable activities | European Commission (europa.eu)

4. MODELS REVIEW AND GAP ANALYSIS

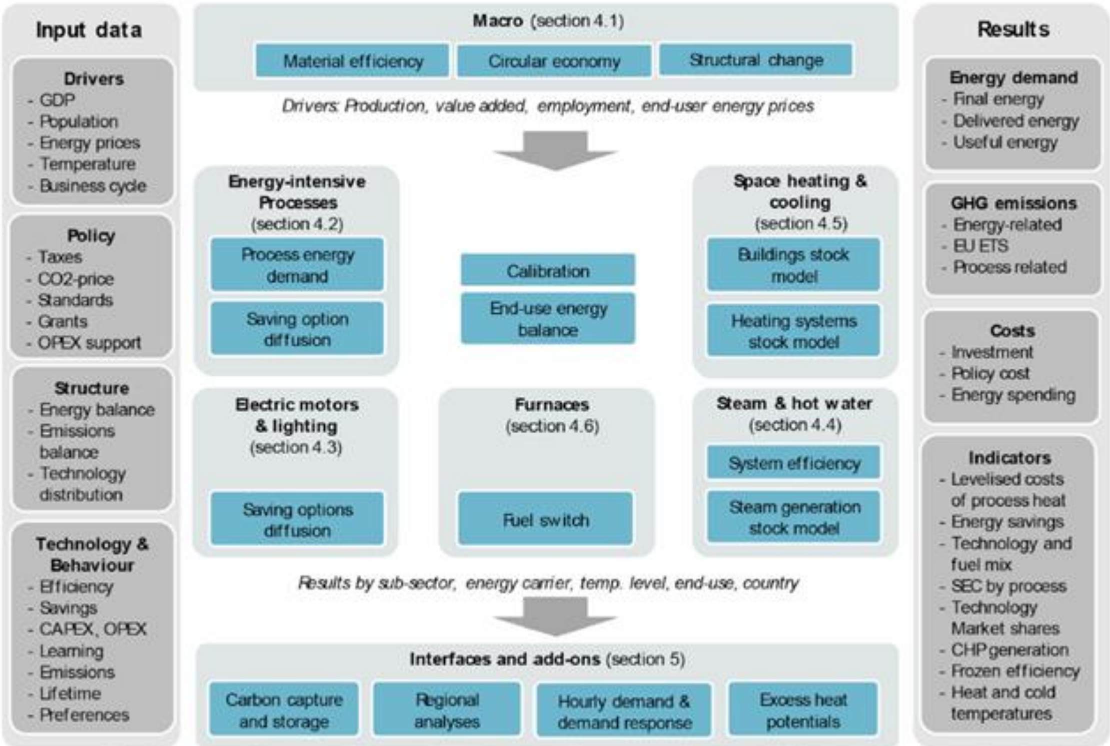
4.1 Industry

4.1.1 Model Introduction: FORECAST-Industry

FORECAST is a bottom-up simulation model used to develop long-term scenarios for the future energy demand of the industry sector (Fleiter et al. 2018). The industry sector module of FORECAST considers a broad range of mitigation options combined with a high level of technological detail. Technology diffusion and stock turnover are explicitly considered to allow insights into transition pathways and speed. The model further aims to integrate policies and considers changes in the socio-economic framework. The model is designed to cover the entire industry sector including major energy-intensive processes with a high level of detail, but also many less energy-intensive sub-sectors and applications. The complete simulation is conducted on the level of individual sub-sectors like iron and steel. The scope of the model is defined by the energy balances and focuses on final energy demand and CO_2-emissions. The model can address various research questions related to industrial energy demand and GHG emissions in the context of technical change. Examples include scenarios for the future demand of individual energy carriers like electricity or natural gas, calculations of energy saving potentials and their impact on GHG emissions, abatement cost curves, ex-ante or ex-post policy impact assessments and low-carbon transition scenarios.

Six sub-models are distinguished in the FORECAST model: macro, energy-intensive processes, space heating and cooling, electric motors and lighting, furnaces, steam, and hot water. Add-ons are also defined that can be applied after calculation of the core model. Different methods are used across the individual sub-models to reflect the heterogeneity and data availability in the respective areas. For example, the energy-intensive processes sub-model uses a simplified diffusion model to reflect the large variety of different technologies, while the steam and hot water sub-model is based on a detailed vintage stock model that distinguishes the age of the technology stock.

Figure 1: Schematic representation of the FORECAST model



t: tonnes, CAPEX: capital expenditures, OPEX: operating expenditures, ETS: Emissions Trading Scheme

Source: Fleiter et al. (2018)

FORECAST input data: comprise the main drivers, policy parameters, structural information and a huge set of technology parameters including behavioral assumptions (see Figure 1). Most of these input parameters are long-term drivers of energy demand and GHG emissions, but business cycles and temperature (heating degree days) are included as well, since these can affect energy demand in a one-year timeframe. Furthermore, the model requires a broad set of input data, which combines a variety of data sources.

The model database was first developed in 2008 and since then has been continuously extended and improved. Energy balances, employment, value added, and energy prices are calibrated to most recent EUROSTAT statistics whenever possible.

Industrial production on country and process level is a major model input and collected annually updated via a variety of data sources including PRODCOM, UN commodity production database, US geological survey, UNFCCC, and industry organisations (World steel association, CEPI, Cembureau, Eurochlor, etc.).

Technology data (costs, efficiencies, age distribution etc.) are mostly not available from public data sources but have been collected from literature or estimated via discussion with industry representatives. The FORECAST technology database is continuously being improved via individual research projects.

Policies and investment decisions: FORECAST allows the simulation of policy impacts. This includes price-based policies like subsidies or taxes, market-based instruments like the EU's Emissions Trading Scheme, but also standards like minimum energy performance standards for individual products. In a more aggregated form, policy instruments such as energy management or audit schemes are also considered by adjusting behavior parameters. The need to simulate the impact of policies also requires detailed representation of investment decisions in the model, because these are the main anchor for policy intervention. They include investments in new steam generation technology, energy efficiency improvements in existing installations, new electric motors but also investments in radically new production plants. Investment decisions in energy efficiency are modelled according to the real-life behavior of companies, which often deviates from cost-optimal decisions under perfect knowledge and faces manifold barriers. Instead, investment decisions are myopic (based on costs and prices in a specific year), and simplified decision rules are applied (like payback time threshold).

Mitigation options and technology detail: achieving deep decarbonisation in 2050 requires a broad range of mitigation options. FORECAST considers the following groups of mitigation options:

- energy efficiency (incremental and radical change),
- fuel switching (to renewable and low-carbon energy carriers) and new low-carbon products and processes,
- carbon capture usage and storage (CCU/S),
- circular economy (recycle, rethink, re-use),
- material efficiency and substitution down the value chain.

These mitigation options are included with a varying level of detail in the individual sub-models. Energy efficiency improvements and fuel switching are modelled endogenously on a technology level in a number of individual sub-models. Mitigation options like material efficiency and recycling are currently considered via exogenous assumptions that need to be incorporated in the scenario definition (see next section).

4.1.2 Gap Analysis and Model Improvement

The following section describes how future projections for industrial production are currently estimated in the FORECAST model considering material strategies (i.e. material efficiency and circular economy) (Herbst 2017; Herbst et al. 2014; Fleiter et al. 2018).

The macro module translates general macroeconomic drivers such as GDP, the population or wholesale energy prices into more specific demand drivers, such as industrial production in tons by process or end-user energy prices that are taken up by the subsequent sub-models. The future development of production output by process (in physical units) is a central driver of energy consumption in the (basic materials) industry, in particular as production is much more closely related to energy demand than economic drivers such as the value added. FORECAST considers more than 70 individual processes and their respective products and semi-products measured in tons of output. This detailed representation of the industry sector at product and process level allows the consideration of specific trends and assumptions concerning material efficiency, the circular economy, the downstream demand for products, saturation effects and structural changes within sub-sectors.

In general, four main groups of products are distinguished in the FORECAST model:

- basic bulk products (e.g. ethylene, chlorine, etc.),
- basic bulk products with primary and secondary production route (e.g. crude steel, aluminum),
- basic products made from raw materials with auxiliary and additive materials (e.g. paper using chemical and mechanical pulp paper with fillers and bleaching additives),
- products from basic materials or basic products (e.g. glass, ceramics, rolled steel).

Three steps are undertaken to develop production projections for each product and semi-product in the current model version:

1. Depending on the characteristics of each product, the main drivers are identified and selected (e.g. per capita demand, gross value added, changing recycling and scrap rates, trends towards accompanying services).
2. Domestic demand and foreign trade developments are estimated depending on the drivers chosen in step one (e.g. per capita demand including saturation effects or the relation of domestic direct demand to gross value added of related and subsequent industries) and the overarching scenario assumptions (e.g. energy carrier prices).
3. Product-specific effects are considered, e.g. intensity of material strategies including the circular economy and material efficiency.

While this approach already allows a transparent inclusion of assumptions on circular economy and material efficiency improvements, however, circularity and its impact on industrial CO_2-emissions/energy demand depends on a variety of different factors, e.g. for the steel industry the future scrap availability and scrap quality as well as other material strategies that reduce end-of-life scrap occurrence and the true steel use of a country (e.g. improved sorting and recycling technologies, design for re-use, prolongation of lifetimes, material substitution, etc.) are relevant. In the current modeling framework of existing bottom-up energy demand models, drivers of industrial energy demand and CO_2 emissions are mainly represented by the physical production of basic materials (e.g., steel, cement, ethylene) in tons and simplified assumptions on recycling, material efficiency and substitution. However, for a detailed analysis of the impact of circular economy on GHG emissions the whole value chain of a good from basic material production to its end-use applications has to be considered.

Table 3: Gap analysis for modeling the new trends in FORECAST

Trend cluster: Green transition	
Green transition	Starting from the existing FORECAST bottom-up model, achieving an EU low carbon circular industry sector until 2050 will be analyzed using a scenario approach. Special focus will also be laid on the medium-term until 2030. For the definition of the scenario, we can benefit from recent EC scenario publications.
Trend cluster: Circular economy	
Circular economy	The project will focus on developing a methodology to assess the impact of circular measures on industrial GHG emissions and energy demand. This methodology will then be implemented for a specific sector, namely the construction industry and building sector, where a reduced scope of actions and policies, prioritized according to their GHG emission potential will be assessed.

Within newTRENDs, the understanding of CE-action impacts (e.g., increased recycling, re-use, material efficiency) along the product value chain as well as on energy demand and CO_2 emission will be improved to better represent such trends in energy demand models. First improvements have already been made in previous projects (Rehfeldt et al. 2020; LeDen et al. 2020b). By adding a more detailed and endogenous representation of material flows and value chains the modeling of deep decarbonization scenario for the industry sector will be improved and the developed methodology will allow the endogenous assessment of circular economy and its adoption by industrial sectors via three main steps (Shanks et al. 2019):

1. Mapping material and energy flows from raw materials to the finished basic product (e.g., cement, steel, ethylene)
2. Mapping material and energy flows from the finished product to its end-use applications including end-of-life (e.g., buildings, infrastructure, plastic)
3. Assigning selected circular economy elements (e.g., increased recycling, re-use, extension of useful life, more efficient material use) with the respective stages in the material flows and along the value chain to assess their potential for material demand reductions and/or energy and CO_2 reductions.

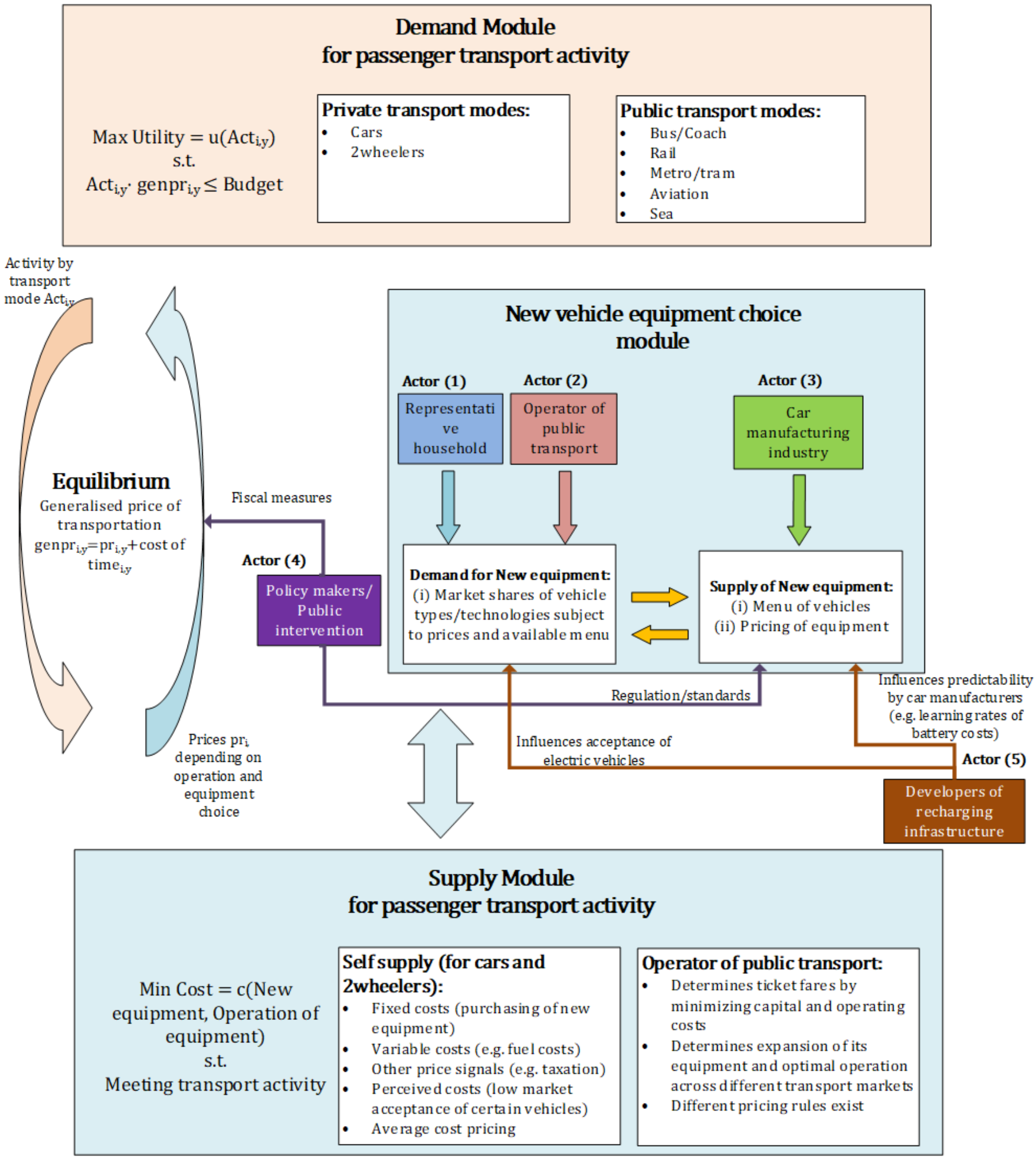
This model improvement will be carried out for circularity measures in the building sector via a stock-driven material flow analysis, which takes into account prospective material demand in decarbonization scenarios. For this purpose, a linkage to the projections of the building stock developments in the INVERT-model will be established.

4.2 Transport

4.2.1 Model Introduction: PRIMES-TREMOVE

PRIMES-TREMOVE is a large-scale economic-engineering model of passenger and freight transport and is part of the PRIMES modeling suite, a family of linked models covering all aspects of the energy system and the demand and supply sectors (Capros et al. 2012) Recent applications of the PRIMES-TREMOVE model are found in Siskos et al. (2018). PRIMES-TREMOVE projects future transport activity, the allocation of mobility to various transport modes (both road and non-road), the choice of technology for the dynamic renewal of the transport fleet, the use of the fleet in various trip types, the consumption of energy, emissions and costs. The dynamic projections cover the period until 2050 and 2070 by 5-year steps and for each European Member State. The base year of the model is 2015. Figure 2 shows a schematic flowchart illustrating the interactions of the actors related to passenger transportation of households, as modelled in PRIMES-TREMOVE.

Figure 2: Schematic representation of passenger transportation modeling



Source: Statharas et al. (2019)

PRIMES-TREMOVE solves an equilibrium problem with equilibrium constraints and involves individual models for the demand of mobility and the supply by transport services and self-supply using private cars. The model solves a structural microeconomic optimization problem for each decision-maker, with embedded technical constraints referring to transport engineering and behavioral parameters reflecting preferences, as well as to policy-related parameters that influence decisions. The decision-making problem runs dynamically in a sequential manner keeping track of all vintages of transport technologies.

Based on evolving technical and economic features of technologies and under the influence of policies, decision makers may purchase new transport means by making choices over a variety of candidate technologies and fuels, and may also consider a scrappage of old vintages. The demanders of mobility follow nested choices to allocate mobility and trip types to the transport modes, determine their rate of use and select technologies for investment. The choice controlling functions follow the discrete choice theory to adequately depict the heterogeneity of behaviors and decision circumstances and thus overcome the limitations of the representative agent hypothesis. The choice functions use utility and cost functions as arguments, which embed several parameters used to reflect behavioral factors (uncertainty, perceived costs, risk perception), as well as penalty factors to reflect technical, infrastructural and resource limitations, and policy-reflecting parameters.

The model simulates the balancing of demand and supply of transport services and self-mobility, through the concept of the generalized cost of transport which includes congestion (time of use), externalities and other factors along with costs. The model solves a mixed complementarity equilibrium problem, using the generalized cost of transport as a dual variable associated with the demand-supply balance. In a way, the model varies the generalized cost, which in turn influences the demand and supply behavioral modeling until reaching a balance. The cost of transport also includes transport fares that the model calculates endogenously on a cost-plus basis, eventually including subsidies for certain public transport means. The mixed complementarity equilibrium also includes overall policy constraints, reflecting policy targets, and uses the associated dual variables to influence demand and supply. The targets may concern emissions, efficiency and renewable energy targets.

Households are modeled to choose new vehicle equipment from a set of fleet and fuel choices provided by car manufacturers. Vehicle purchasing prices, as set by the manufacturing industry, change dynamically following cost-efficiency improvement curves that draw from engineering studies. Car manufacturers price their portfolio of electric vehicles (EVs) depending on the evolution of battery costs. Households compare costs, convenience and congestion to make a decision, which also depends on penalty factors in case the density and coverage of refueling/recharging infrastructure are not adequate. The model also includes subjective factors as additional costs. In this manner, the model captures traveling inconvenience (range anxiety), technical risk perceptions (regarding maintenance and performance), imperfect information and the opportunity cost of funding capital costs to reflect the consumer conservatism towards choosing a new technology like an EV. The various cost elements constitute components of the generalized unit cost of transport services.

The model represents public policy based on fiscal instruments (e.g., subsidies, tax exemptions, etc.), tolling and congestion pricing, CO_2 or efficiency standards applying on vehicle manufacturing, overall policy targets and the extent and timeliness of infrastructure development. The model applies a penalty mechanism specifically by vehicle technology type, to discourage the production of vehicle varieties that do not comply with the standard, CO_2 or efficiency or both. The model captures the effects of the refueling and recharging infrastructure by splitting the trip types into stylized geographic areas (i.e., metropolitan, other urban, highways, and other roads). In addition, the model includes public policy, e.g., campaigns aiming to increase the awareness of the new technology and reduce the subjective surcharges and thus enable the emergence of the new technology in the markets.

4.2.2 Gap Analysis and Model Improvement

The following focuses on key trends, which are relevant to the modeling of the transport sector. We present how these trends are currently modeled and tentatively propose ways to model other trends, which are not currently reflected in the modeling. Often, when possible, a comparison against the literature is offered.

Table 4: Gap analysis for modeling the transport sector in PRIMES-TREMOVE

Trend cluster: Digitalization

Flexible transport services Intelligent transport systems and infrastructure Autonomous vehicles	Digitalization in transport has a wealth of interpretations and strong linkages with other trends. The PRIMES-TREMOVE transport model reflects aspects of digitalization in several ways, also in accordance with other trends such as shared economy. Capturing some effects are possible via modal shifts towards public means of transport (simulating Mobility as a Service effect), increased load factors/occupancy rate (simulating the development of carpooling in the shared mobility context), increased car mileage and somewhat improved energy efficiency (representing the increased utilization of autonomous cars) and decrease in urban transport demand due to flexible work and e-commerce. The extent of the abovementioned changes (e.g., the % increase in the occupancy rates) needs to be aligned/ validated with external sources which trace back to specific case studies and be generalized to the more high-level resolution of the model. Ultimately, modeling such changes in an endogenous ways in a transport model represents a challenging task, which needs to associate specific patterns of changes against specific drivers. Such aspects will be considered in WP7. The literature offers examples of model-based capturing of digitalization. For example, Noussan and Tagliapietra (2020) propose a scenario analysis by evaluating the potential effects of digitalization on mobility demand, energy consumption and CO_2 emissions under two main pathways, categorized as responsible and shellfish digitalization. These pathways follow different

	drivers, including users' behavior, economic conditions and transport and environmental policies. They use a deterministic, rather simplistic model calculating linearly the impacts of the transport given its demand. The potential effects of digital technologies have been grouped in three areas: Mobility as a Service, shared mobility and autonomous vehicles. They are implemented via modal shifts relative to public means of transport or carpooling services, shifts relative to urban or non-urban trips and changes in load factors. The use of automated vehicles can also imply a more productive/enjoyable trip for the individuals. In transport terms, this could be reflected as a reduced value of time spent over transportation. The latter aims to reflect individuals' opportunity cost of the time spent during traveling. Hence, in the case of automation, the individuals can utilize this time for other purposes, which might in turn lead to rebound effects.
Trend cluster: Sustainable cities	
Sustainable transport	The PRIMES-TREMOVE model considers a split of the overall transport activity by mode into four aggregate areas/road links (urban, metropolitan, inter-urban areas and motorways). Urbanization is reflected in the model as a further uptake of urban transport activity and increased number of commuting trips. The model includes a travel time function associating traveling time with transport network infrastructure; yet it lacks the resolution of transport network models. On the other hand, the model simulates decarbonization scenarios with high or even complete penetration of electric vehicles in the urban areas and this leads to reduction in air and noise pollution. Shifts to public transport are also incorporated in the modeling. Further enhancements on the modeling of micro-mobility or soft modes such as e-scooters are also under consideration. Sustainable cities can be modeled in different concepts relatively to the model conceptualization, the activity disaggregation, and other attributes incorporation. For example, Reul et al. (2021) develop an activity-based transport demand model investigating the effects of new trends or behavioral changes, such as urbanization, aging of the population and trends related to effects deriving from the COVID-19 health crisis. The activity and the mode choice are implemented via a nested logit model, while the destination choice is approached with a conventional gravity model. They determine the number of SAVs and the total mileage of the SAV fleet, by employing different dispatching algorithms for the car sharing and the ride-sharing scenarios. Strulak-Wójcikiewicz and Lemke (2019) develop a simulation model for evaluating the sustainability of urban transport in social, economic, and environmental dimensions. They integrate numerous quantitative and qualitative indicators of the sustainable development of urban transport, estimating them simultaneously in a dynamic way.

Trend cluster: Green transition

Uptake of low and zero-emission technologies in transport	PRIMES-TREMOVE includes decarbonization policies and green pathways in road and non-road sectors for successfully "greening" the overall transport sector. The option for advanced electric and hydrogen technology uptake in aviation, navigation and rail transportation is available, along with the uptake of synthetic e-liquid fuels and biofuels. The uptake of the latter two can be derived endogenously via price- and quantity-driven competition mechanisms or enforced as mandatory quotas in the final fuel blending filling the vehicle tank. Taxation policies on specific fossil fuels can be applied to penalize conventional technology uptake as well as subsidization of clean-fueled vehicles for an enhanced and combined effect towards deep emission curbing. Furthermore, specific fuel technology ban enforcements, such as conventional diesel cars in metropolitan areas, can also be implemented. The EU emission trading system is fully incorporated in the model, covering air transportation, and can be further expanded to apply to the other transport modes (e.g., road transport).
Fuel switching in the road freight, aviation and shipping sector	The transition towards environmentally friendly practices in transport (decarbonization of the sector) is reflected in many ways in PRIMES-TREMOVE. Clean fuel vehicle technology adoption (electric vehicles, hybrids, CNGs, fuel cells) and advanced powertrain ICE technologies with lower energy consumption are fully incorporated to the model. A Weibull vehicle choice function that considers the density of alternative fuel infrastructure, battery costs, electric range, fuel economy, external costs (air pollution, road safety, noise etc.), intangible costs, societal trends and fuel prices aims to capture the consumer idiosyncratic behavior, simulating the impact of various "green transition" policies. Moreover, CO_2 standards are modelled to apply in the automobile industry, enforcing targets for the newly marketed vehicles, with possible application to not only cars and vans, but also trucks, two-wheelers and buses. The modeling considers in a simultaneous manner the interrelations at the stage of the new transport equipment choice along with the selection of transport modes. The latter is obtained through the use of a nested CES utility and cost function for passengers and businesses. In the case of a significant fuel switching for a specific transport mode (e.g., shift from diesel to electric trucks), it could lead to an increased competitiveness of the mode compared to alternatives such as rail.
Green transition (combination of subcategories)	Integrated energy and transport models incorporate green transition mechanisms and modeling approaches in order to provide a more accurate representation of the future transport activity and energy system status under specific assumptions, seeking the least-cost energy system pathway to meet future energy service demands. Models such as TRAVEL (Girod et al. 2012) and CIMS (Horne et al. 2005) use discrete choice functions

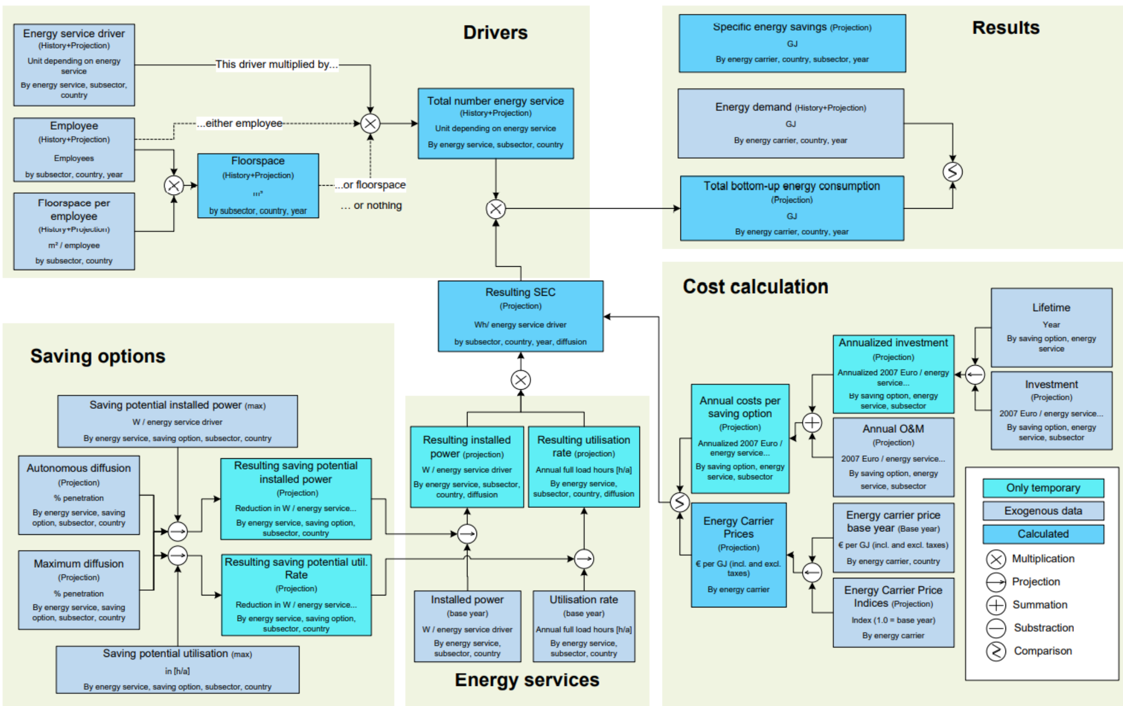
	to simulate the technology uptake considering various policy representing parameters in a similar way with PRIMES-TREMOVE as described above. EPPA (Karplus et al. 2013) use CES, to capture the substitution between conventional internal combustion engine vehicles and alternative fueled vehicles, while MESSAGE-transport (McCollum et al. 2014) uses disutility costs to consider consumers' discomfort when adopting alternative fuel transport technology, associating it with lack of refueling infrastructure, range anxiety, and scarce vehicle model variety. The model BLUE (Li et al. 2015) uses hurdle rates which are higher discount factors associated with new or not fully commercial technologies, expressing difficulty and uncertainty in market acceptance of new technologies. All these modeling techniques aim to capture consumer behavior when choosing a transport technology by also including intangible costs affecting the consumer's decisions.
Trend cluster: Decentralized work	
Decentralized work	Flexible work and e-commerce can be simulated in the PRIMES-TREMOVE model only as an exogenous decrease in urban transport activity demand. This type of input needs to be validated and checked against wider than transport frameworks. This has to take into consideration demographic changes, household decisions to live in inter-urban regions, etc. Methodologically, this trend can only be implemented in an exogenous fashion in a transport-dedicated model. Work of a similar nature has been presented by Noussan and Tagliapietra (2020).
Trend cluster: From owning to sharing	
Car sharing	This trend is also included in PRIMES-TREMOVE model. In the model, shared vehicles are modeled via increased load factors (simulating the development of carpooling in the shared mobility context) and increased car mileage (improvement of fleet utilization). In the next steps, the model utility functions will be modified to simulate the uptake of shared economy transport services. Furthermore, the decision tree of passenger travel demand to include nodes representing those services, introducing competition between this newly introduced mode of transport versus public transport. For the modeling purposes, shared economy transport services need to be priced accordingly. To this end, we need to define how companies charge shared vehicles users, as there are currently different payment schemes (subscription fees, single tickets, etc.). For this purpose, To this direction several modeling practices from the literature, such as Fagnant and Kockelman (2014), Boyacı et al. (2015), Acheampong and Siiba (2020), Scorrano and Danielis (2021), Said et al. (2021), will be explored and combined to provide a more rounded approach to exploring this cluster.

4.3 Tertiary Sector

4.3.1 Model Introduction: FORECAST-Tertiary

The FORECAST Tertiary model is a bottom-up energy demand simulation model, which calculates building- and process-related electricity demand as well as fuel-specific heating demand for tertiary sector buildings. The model relates energy demand drivers, such as floor area per employee, with specific energy services such as lighting and potential saving options for these energy services together with their associated costs to calculate final energy demand per country and tertiary sub-sector (see Figure 3).

Figure 3: Schematic figure of the FORECAST-Tertiary electricity demand model



Historic trends are represented in the model and projecting them into the future leads to the scenario-specific energy demand results. In the case of new trends, assumptions need to be adjusted or newly implemented to take up specific demand drivers and related energy services. In the following gap analysis, we will further elaborate which of the described new trends are missing in the current model version and which of the new trends can be implemented given the current set-up of the model.

4.3.2 Gap Analysis and Model Improvement

Based on the trend analysis for the tertiary sector described in Section 3.3, we further elaborate how these trends have been represented in the FORECAST-Tertiary demand model so far and introduce possible pathways of how to represent these trends in the future. Table 5 gives an overview and explanation of the trends described in the trend analysis of Section 3.3.

Table 5: Gap analysis for modeling the tertiary sector in FORECAST-Tertiary

Trend cluster: Digitalization

Online Shopping and Food Delivery	Not yet integrated; integration of new demand drivers needed. This trend is affecting the current wholesale and retail trade sector in different ways and, therefore, these commercial sectors need to be better differentiated: • Currently, in FORECAST Tertiary the specific floor area per employee is the driver for energy demand projections for the wholesale and retail market based on studies analyzing the past trends, which are extrapolated into the future. If small shops are replaced due to the shift to online shopping, the respective number of employees will change as well as the specific floor area per employee, as larger grocery stores will adjust their number of employees and type of services. These changes need to be reflected in the newTRENDs scenario analysis. In addition, to better represent the demand trends for large storage facilities and warehousing (of the logistic sector), these sub-sectors need to be split in the model preparation and data collection phase. • It is likely that some of the smaller shopping surfaces have already disappeared forever and it is likely that in many countries more surfaces will disappear. Therefore, the demand structure of the commercial sub-sector will change. However, as in inner cities smaller shops might be converted into workshops, coffee shops, bars etc. to create interesting leisure space, such changes will influence the energy demand and e.g., surfaces in the respective sub-sector of gastronomy, which also needs to be updated for the newTRENDs scenario analysis. • The implementation of goods-related indicators (e.g., in tons per year or similar) will be evaluated to be able to exchange data with e.g., the transport sector to better represent the shift towards goods distribution by delivery companies versus private grocery shopping.

	The status of the model does not represent any trends regarding food delivery and convenience food. It is likely that more food delivery will shift energy demand from the household sector into the demand sectors of gastronomy and retail trade. In these sectors, energy demand for cooling, food processing and cooking will therefore increase. Additionally, the demand for additional transport needs to be reflected in the transport model. However, at the current state it remains unclear if this trend is of high impact on overall energy demand, as a first country-based analysis did not provide sufficient indication of such relevance (Jakob et al. 2019).
Cloud-based Services, Big Data and 5G	Partial integration of past development of increasing data center demand. Based on the historic growth of new data center demand starting in relevant terms after 2016, planned new data centers in Europe are currently considered in FORECAST Tertiary. However, to further elaborate on the effective demand growth and the potential interlinkage with other decentral ICT demands in the different sub-sectors, the model is foreseen to be updated: • Either by implementing new demand drivers such as the degree for further virtualization, the number of physical servers installed, the amount of mobile processed data, or the size of the storage facilities to better represent the energy demand from ICT and cloud-based services. • Additionally, related demand for cooling purposes must be adjusted under consideration of country-specific values for optimal power usage effectiveness. The utilization of waste heat from ICT equipment might be addressed. However, the analysis of waste heat management is not part of the work done.
Trend cluster: Green Transition	
Rebound effects	Rebound effects of new trends need to be integrated; integration of new demand drivers needed. The representation of the so-called energy efficiency gap in buildings is already implemented in FORECAST Tertiary. In short, if buildings are insulated, the indoor temperature will effectively be increased compared to the reference temperature in the building code and, therefore, energy demand remains higher in comparison to the calculated energy demand reductions based on the refurbishment measures. Implementing new services in the model will likely lead to similar effects that energy savings or shifts in the demand pattern might be compensation for by additional energy demands or less demand reductions as expected. Therefore, the main newTRENDs will be investigated for such rebound effects and respective efficiency losses will be implemented in the model. The

	interlinkage to other models will be considered as well as rebound effects might become visible in other demand sectors. Examples exist where such rebound effects can be observed: • People are ordering more goods in the online shop as needed and send back parts, which do not fit. Therefore, transportation and storage demand are higher, including additional waste compared to buying the same goods in a large store. • People might continue driving to the grocery stores although online shopping is becoming more relevant for these people. Therefore, the demand for transportation is increasing overall, as additional delivery tours are needed to supply the online ordered goods, which are not bought at the same time, when grocery shopping is taking place.
Trend cluster: Decentralized Work	
Decentralized Work	Not yet integrated; adjustment of existing model parameters needed Currently, the simulation results are based on input assumptions on the average number of working hours per sector, the occupation of buildings, the number of employees and the related energy reference area and the installed capacity needed to supply the final energy demand. Therefore, to reflect changes in the occupation of buildings, several scenario-specific adjustments are needed: • The adjustment of specific floor area per employee is likely to decrease, as more people will work at least part time from home. Companies will try to reduce the rented/owned overall office space to reduce respective costs. Depending on the sub-sector and country, these figures are likely to vary. • Besides the adjustment of specific floor area per employee, the occupation of buildings might change in sub-sectors where the overall office space cannot be optimized in a simple manner (desk sharing). It will be evaluated if e.g., small office firms are less likely to reduce overall rented surfaces compared to large companies due to different decision parameters. • Depending on the structure of working from home, working hours in the office might vary in terms of working hours per day or week within the office. This adjustment influences e.g., the number of hours where lighting is needed. • Depending on the work structure, it currently remains open if installed capacities for e.g., lighting, ventilation, cooling, etc. can be adjusted to reduce overall energy demand.

	Depending on the sub-sector demand structure and their related changes due to working from home, some of the sub-sectors might be split to better represent the share of people with the possibility of working from home compared to other services functions, which cannot be provided in the home office. This split might be relevant for large services sector companies where front desk work and back-office tasks can be separated and respective employees have the possibility to work from home (back-office) or not (front-office).
Trend cluster: From Owning to Sharing	
From Owning to Sharing	Not yet integrated; integration of new demand drivers needed This trend is currently not represented in the FORECAST Tertiary model. As this trend introduces new services and related energy demands, these need to be implemented in the services sector as well as new drivers need to be defined for such services. • In case of AirB&B-related services, the driver of energy reference area remains a proxy whereas the use hours of such facilities and the specific energy demand needs to be revised. This trend is cross-sectoral as household surfaces as well as the hospitality sector are influenced. • For other new services, the specific energy demand per employee needs to be derived and implemented in the model code.
Trend cluster: Circular Economy	
Circular Economy	Not yet integrated; integration of new demand drivers needed To support the calculation of the circular economy in industry related to the materials need from the tertiary building stock, the FORECAST Tertiary model needs to provide related information on construction material demand. This information is currently not available from model calculations. However, based on the existing model set-up the following adjustments can be made: • Currently, the model provides information on the surface areas, which are refurbished, for different building types. Based on the existing structure and energy-related information (e.g., U-values) the demand for insulation material can be estimated and provided. • With information on the activity of demolition and construction of new buildings and the related material need for the building structure, total material demand can be estimated. Thus, the materialization for different scenarios variants can be calculated for different scenarios.

Trend cluster: Demographic Change

Elderly care	Not yet fully integrated; adjustment of existing model parameters needed Information will be exchanged with the household sector to better represent the interlinkages with elderly people staying longer at home and the related impact on the demand for pension- or nursing homes. • Currently, the model is using the specific energy and surface demand per employee in the respective tertiary sector to estimate energy demand for e.g., nursing homes. Changes in demand shifts and new demands (more demand for motor-supported beds, etc.) will be evaluated.
New labor	Not yet integrated; integration of new demand drivers needed Demand drivers based on the digitalization of services are currently not or underrepresented in the model. To update the model output, we will analyze the specific energy demand for such job profiles (e.g., equipment rate of laptops, screens, etc.). Additionally, the exchange with other demand sectors (e.g., transportation or industry) needs to be kept in mind as digitalization or servitization is likely to come along with a job reduction in manufacturing or production.

4.4 Residential Sector

4.4.1 Model Introduction: FORECAST-Appliance

FORECAST-Appliance calculates the energy consumption of appliances in the residential sector. It is a simulation model driven by the number of households/dwellings with yearly resolution, covering 7 appliance groups, 23 appliances, and 47 appliance technology types, as listed in

Table 6. Following the Ecodesign Directive (2009/125/EC), FORECAST-Appliance further distinguishes each appliance technology type into multiple efficiency standards (e.g. A+++, A++, etc.). So in total, there are four layers to classify all the appliances of households: appliance group, appliance, technology and efficiency class.

Table 6: Coverage of FORECAST-Appliance model

Appliance Group	Appliance	Technology
White Appliances	Refrigerators	Refrigerator (average)
	Freezers	Freezer (average)
	Washing machines	Washing-machine (average)
	Dryers	Drier (average)
	Dishwashers	Dishwasher (average)
Cooking	Stove	Electric-Stove, Oil Stove, Coal Stove, Gas Stove, Wood Stove
ICT	Televisions	S (TV-Sets), M (TV-Sets), L (TV-Sets), XL (TV-Sets)
	Computer screens	CRT (PC Screens), LCD (PC Screens), Plasma (PC Screen)
	Set-top boxes	ESTB (Set-Top-Boxes), ESTB/PVR (Set-Top-Boxes)
	Laptop computers	Laptop (average)
	Desktop computers	Desktop PC (average)
	Modems	Modem/Router (average)
Small Appliances	Vacuum-Cleaner	Vacuum-Cleaner-Canister, Stand-Vacuum-Cleaner, Vacuum-cleaner-Wireless
	Coffee-machine	Coffee-machine (average)
	Iron	Iron (average)
	Toaster	Toaster (average)
	Hair Dryer	HairDryer (average)
	Microwave	Microwave (average)
	Exhaust Hood	ExhaustHood (average)
Lighting	Lighting	Light-Bulb, Halogen Lamp, Energy Saving Lamp, Fluorescent Lamp, LED
Circulating-Pumps	Circulating-Pump	KEUP_constantly, KEUP_variable, KIUP_constantly, KIUP_variable, GEUP
Cooling	Air conditioning	Mobile Air-Conditioning, Reversible Air-Conditioning, Air-Conditioning Split
	Ventilation	Ventilation (table), Ventilation (stand), Ventilation (tower)

Source: Elsland (2016)

Following this classification, FORECAST-Appliance simulates the diffusion of appliances in three layers (Elsland 2016):

- First, the diffusion of "appliances (2nd layer)" is modeled as "ownership dynamics" following the Bass model (Bass 1969), extended by considering the "rivalry substitution" (Mahajan and Peterson 2010) and "disposable income elasticity" (Horsky 1990) effects. Second, for each appliance, the share of different "appliance technology types (3rd layer)" (e.g. monitors with different technologies, such as CRT, LCD and Plasma) are exogenously calibrated based on empirical data.
- Third, choice of households between different "energy efficiency classes (4th layer)" is modeled following the nested multinomial logit model (Train 2012). The options with "higher utility (i.e. higher efficiency)" are chosen with higher probability. As a result, following the Ecodesign Directive, the steadily increasing minimum energy standards will in the long-run lead to an increase in the efficiency of appliances in the stock.

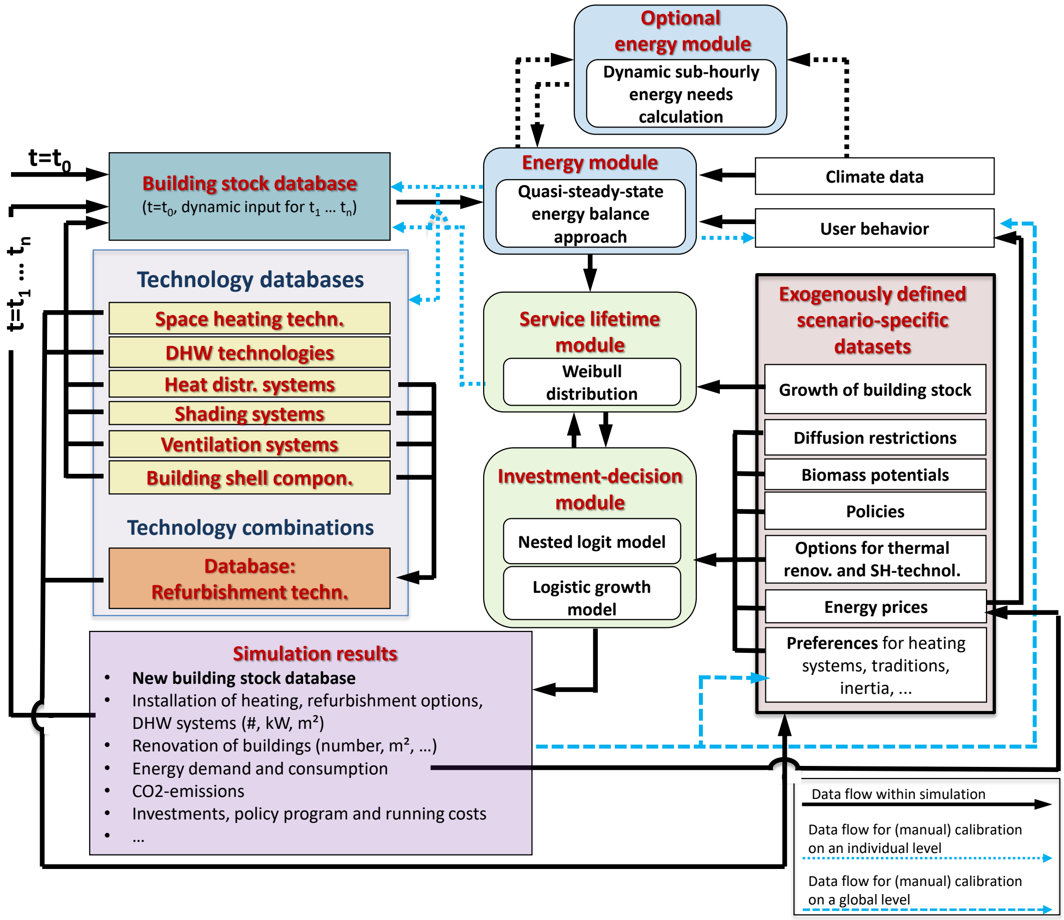
In the end, driven by the household/dwelling number, FORECAST-Appliance calculates the annual energy consumption of each appliance by multiplying the appliance stock, operation power, and operation duration. Summing up all the appliances, FORECAST-Appliance provides the final energy consumption.

4.4.2 Model Introduction: INVERT

The **building stock model Invert/EE-Lab** is a techno-socio-economic bottom-up building stock model to develop scenarios of building-related heating and cooling demand and supply. It is based on a highly disaggregated description of the building stocks in the different countries of the EU (+ Norway, Iceland, Switzerland, UK) including type of building, age, state of renovation, existing heating systems, user structure as well regional aspects such as availability of energy infrastructure for e.g. district heating or natural gas on a sub-country level. It simulates investment decisions in the building shell and the heat supply and distribution systems via a combination of a discrete choice approach and technology diffusion theory. This makes it possible to study the influence of various side-conditions including policy measures on the decisions of the actors. Thus, Invert/EE-Lab is designed to simulate different scenarios (price scenarios, insulation scenarios, different consumer behaviors, etc.) and their respective impact on future trends of energy demand and mix of renewable as well as conventional energy sources on a national and regional level. More information is available on www.invert.at or e.g. in Müller (2015), Kranzl et al. (2013), and Kranzl et al. (2019).

The basic structure and concept are described in Figure 4.

Figure 4: Overview structure of Simulation-Tool Invert/EE-Lab

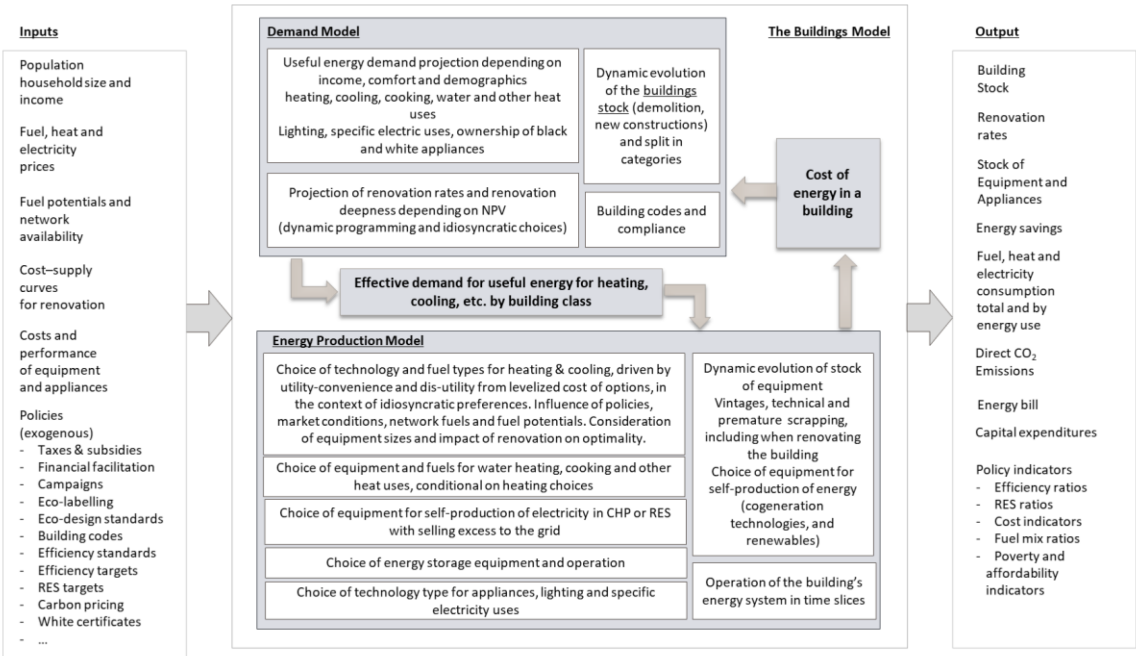


4.4.3 Model Introduction: PRIMES-BuiMo

The PRIMES-BuiMo projects the future energy demand in the buildings of the residential and services sectors. It focuses on the dynamic simulation of the renovation decisions and the depth of building renovation, the choice of technology types for covering the energy end-uses, including space heating, air cooling, cooking, water heating and different electric appliances (Fotiou et al. 2019).

PRIMES-BuiMo opts for a hybrid economic-engineering approach, covering the dynamics of stock evolution and placing great emphasis on modeling behaviors, as well as on policies influencing behaviors (see Figure 5). Hence, the model represents idiosyncratic behaviors and (non-) market barriers, while also providing a high-resolution disaggregation of the building stock. Furthermore, it classifies the building stock in many different categories (termed “building classes”) based on house/building type, geographic location, age of construction, income class or services sub-sector. Thereby, the model projects into the future energy demand, using a dynamic simulation of the renovation of the buildings' shell, together with the choice of technology and fuel types for the different uses of energy (Fotiou et al. 2019).

Figure 5: PRIMES BuiMo description



Source: Fotiou et al. (2019)

The model formulates the individual decision as a structural microeconomic optimization problem of an agent, involving maximization of consumer's utility under budget, technical, economic, and policy-related constraints (Fotiou et al. 2019). Parameters varying by agent represent the heterogeneous behaviors of consumers.

The PRIMES-BuiMo includes a comprehensive taxonomy of market and non-market barriers hampering energy efficiency investment, which are commonly neglected in pure engineering calculations, and result in what is sometimes considered as irrational behavior of consumers, bounded in any case. Irrational behavior, which challenges conventional microeconomic theory, is for some authors the reason for limited rates of energy-efficient renovation of buildings (Fotiou et al. 2019). The approach followed in PRIMES-BuiMo consistently integrates non-market barriers in the microeconomic modeling framework, which, combined with idiosyncratic preferences, can capture poor energy efficiency choices and still represent rational behaviors. In other words, the seemingly irrational behavior of consumers may be well explained through the concept of non-market barriers. For the PRIMES-BuiMo modeling, we decided to represent a formulation founded on the micro-economic framework enriched with representations of (market and non-market) barriers and idiosyncratic behaviors.

Despite the high resolution of buildings segmentation in PRIMES-BuiMo, the consumer behaviors within each class of households are still not homogeneous. Idiosyncratic behaviors persist within each class, and thus the modeling approach has to capture this heterogeneity as well (Fotiou et al. 2019). For this purpose, the model applies a discrete choice theory formulation within every consumer and building category.

4.4.4 Gap Analysis and Model Improvement

4.4.4.1 FORECAST-Appliance

FORECAST-Appliance focuses on the electricity that is consumed by appliances in households. Therefore, regarding the clusters and trends summarized in Section 3.4, the FORECAST-Appliance model is mostly affected by the cluster of Digitalization. The gap analysis and model improvement is provided in Table 7.

Table 7: Gap analysis for modeling the residential sector in FORECAST-Appliance

Trend cluster: Digitalization	
Diffusion of network-connected devices	To consider the diffusion of network-connected devices and relevant energy consumption, FORECAST-Appliance is extended to cover these appliances, as well as their multiple working mode. Furthermore, the demand for data storage and transmission for the upstream sectors will also be provided.
From consumers to prosumagers	This trend implies several model improvements, including the integration of PV and batteries, smart appliances (shiftable load), heat pumps and thermal storage, and smart home energy management systems. In FORECAST-Appliance, we will extend the model and cover the smart appliances, including dishwasher, washing machine, and dryer. Furthermore, Fraunhofer ISI and TU Vienna will develop a joint optimization module for an individual household, to integrate all of its technologies and optimize the hourly system operation. In this way, the households' prosumaging behavior is captured and evaluated. Based on this, the optimization result will be used in FORECAST-Appliance and INVERT to simulate the long-term investments up to 2050.
Trend cluster: Decentralized work	
Decentralized work	In the hourly optimization module, we will consider the lifestyle of individual households, including their "work-from-home" features. Thus, the hourly energy demand will be altered to account for people staying and working from home.

4.4.4.2 INVERT

Due to its nature as techno-socio-economic bottom-up model, Invert/EE-Lab covers technical specifications and restrictions as well as the heterogeneity of decision makers. Thus, the model is able to cover a wide range of policy related questions, in particular regarding the possible impact of technology uptake, the possible impact of different policy interventions and the long-term dynamic of the building stock and related energy demand and supply. Recently, due to the link with the Hotmaps district heating model, a higher spatial granularity and a better representation of the district heating sector could be achieved (Fallahnejad et al. 2018; Müller et al. 2019).

However, the modeling of hourly demand profiles up to now was done only through a static load profile for various building types and climatic regions. Thus, the dynamic behavior of prosumagers and the possibly resulting demand profiles were not yet properly represented. This is a gap, which will be closed within this project. This is strongly related to the trend clusters digitalization and sustainable cities. However, also the other trend clusters have a significant impact.

Table 8: Gap analysis for modeling the residential sector in Invert

Trend cluster: Digitalization

Digitalization Smart metering Electrification of heating	In the context of the increasing electrification of heating, digitalization and smart metering has the potential to significantly change the role of buildings in the energy system. **Existing feature:** Some smart devices like smart thermostats are already explicitly implemented in the model (Müller et al. 2018). **New developments:** Within newTRENDs, the possible future behavior of prosumagers and the resulting load profiles will be integrated in the building stock analysis. Special attention will be put on the flexibility of the space and water heating end-use (and to some extent on space cooling). Smart control devices and – through increased digitalization – automated aggregated control of heat pumps are an important aspect, which will be considered in the model extension. In this context, Fraunhofer ISI and TU Vienna will develop a joint optimization module for an individual household, to integrate all of its technologies and optimize the hourly system operation. In this way, the households' prosumaging behavior is captured and evaluated. Based on this, the optimization result will be used in FORECAST-Appliance and INVERT to simulate the long-term investments up to 2050.

Trend cluster: Sustainable cities

Increased urbanization	Urbanization is a key driver for the mix of buildings and the possible share of district heating. **Existing feature:** Currently, the model is able to capture the evolution of different types of buildings (i.e. the share of larger apartment buildings vs single-family houses) through exogenous input. Moreover, the current and possible future share of dwellings within urban, sub-urban and rural areas can be explicitly distinguished, thus having an impact on the possible role of different energy carriers, in particular district heating. **New developments:** No strong focus is foreseen within the newTRENDs-modeling of the residential sector regarding this trend cluster. If data on the expected urbanization were available, they could be integrated in the modeling.

Trend cluster: Green transition

Green transition	Multiple aspects of this trend cluster may affect the transition of the building stock, e.g. the use low-carbon insulation material, the uptake of renewable energy communities and the role of buildings in this process or the increased role of prosumaging of building occupants. **Existing feature:** The current state of the model is able to simulate the transition towards low carbon heating and cooling systems and a more efficient building envelope. **New developments:** As explained under “digitalization”, the transition towards a higher share of prosumagers will explicitly be integrated in the analysis. We will also discuss selected aspects of renewable energy communities. Distinguishing other building materials and, in particular, insulation materials up to now is no strong focus in the project. However, there is a clear link to the industry sector, in case that the building stock’s demand for different construction materials would change. This link would be relevant to be further investigated.

Trend cluster: Decentralized work

Decentralized work	Increased homework will shift some (floor and energy) demand from offices to the residential sector with corresponding implications on total demand and resulting load profiles. **Existing feature:** The current model foresees the option to exogenously foresee a shift between floor area of different building end-uses and also a gradual shift of user profiles.

	New developments: In order to integrate this aspect, only moderate model developments as such would be required. However, solid data on the expected shifts between different building categories' floor area and related user profiles would be needed.
Trend cluster: Climate change & behavior	
Increased awareness of citizens Energy and climate policies	Behavioral aspects are highly relevant for the building stock's energy demand and evolution in the future. This concerns both short-term energy-related behavior like required indoor temperature levels, ventilation behavior etc. and long-term investment behavior regarding the choice and willingness to pay for different technologies and measures. **Existing feature:** Currently, the model foresees the consideration of agent specific decision rationales, like different interest rate or preferences. **New developments:** If data on the possible evolution of these decision criteria and rationales were available for different agent groups, they could be implemented in the model.
Trend cluster: Socioeconomic dynamics	
Energy poverty Just energy transition	**Existing feature:** As explained above, the model is able to capture decision criteria of different agents. A typical distinction of agents is via their income and related budget restrictions. **New development:** Main challenges in this respect are the expected evolution of agents in different parts of the building stock and also the dynamic changes of population groups in different buildings, including aspects like gentrification of districts and people with different background moving between building types. This is not foreseen as explicit focus in the project but is considered as interesting possible future model development.
Trend cluster: Green finance	
Alternative means for green finance Increasing investment expenditure in energy efficiency	Availability of favorable financing schemes is very relevant for capital-intensive measures like building retrofitting. **Existing feature:** Availability of green financing schemes can be implemented in the current model through implementation of lower interest rates (potentially for different types of measures and different types of agents).

Trend cluster: Demographic change

Aging population	Demographic changes have potential strong impact on user behavior, user profile and demand for floor area in different types of buildings, including homes for elderly people and buildings in the health sector. **Existing feature:** The changes described above can be implemented in the Invert model e.g. through gradual change of user profiles and the number of buildings and related floor area in different building categories. **New developments:** The described changes in model input data are not foreseen as a major focus in the project. In case that corresponding data is available, it could be integrated in the model.

Trend cluster: Great Depression II

Reduction in disposable income	The reduction in disposable income may have significant impact on the ability to invest in energy saving measures and new heating systems, in particular if they are more capital-intensive. This may be true in particular for some parts of the population. **Existing feature:** As described above, the model currently foresees different decision criteria and restrictions for different agents (i.e. building owners). In case that a reduction in disposable income is expected at least for some groups of the population, this could be integrated through an increase in the corresponding agent class. **New development:** No model development as such would be required, rather integration of new data. Currently, this trend is not foreseen as major focus within the modeling of the residential sector in the newTRENDs project.

4.4.4.3 PRIMES-BuiMo

Combining the microeconomic components to represent the idiosyncratic behaviors of the citizens included in the PRIMES-BuiMo, allows modeling their decision-making process regarding the envelope renovation and the upgrade of the technical building systems (heating & cooling, appliances) in the buildings sector (both residential and tertiary). The technical dimension of the problem is also taken into consideration through engineering constraints regarding the operation of both the appliances and the heating & cooling equipment. At the same time, exogenous policy signals are also included and influence the choices regarding envelope renovation, heating and cooling equipment and appliances. Consequently, the existing formulation of the PRIMES-BuiMo renders it suitable for studying a wide range of policies, trends and their impacts.

Identification and analysis of New Societal Trends and their clusters–especially regarding prosumaging–indicates that, while several of them are already considered in the PRIMES-BuiMo, improving the existing residential model will allow studying the impact of prosumaging in greater depth: Investment decisions in local generation units using renewables as well as implementation of demand response schemes facilitated by the existence of smart meters are two key aspects of prosumaging that require developing new model features.

The effects of prosumaging will be developed as an add-on tool linking the supply side of the PRIMES model (PRIMES Power and Steam) to the building demand side of the model (PRIMES-BuiMo). The aim is to capture both the prosumager decision-making process with regard to investments, operation of appliances, and heating & cooling equipment when the prosumager is transformed into a net producer selling excess energy to the grid, as well as the economies of scale incurred when several such prosumagers are managed locally by one entity to form a block.

This section includes for each identified trend cluster from WP2, how the trends are already covered in the PRIMES-BuiMo and, where relevant, how the new tool will improve the representation:

- Whether the trend cluster is planned to be considered by the model;
- If the trend cluster will be considered by the model and is an existing feature, a short description of how this is already done and how it will be applied in the prosumager model;
- If the trend cluster will be considered by the model and is a new/additional feature, a short description of how this will be incorporated in the prosumager model;
- Each trend to be considered by the model (either as an existing or as a new feature), requires proper handling in terms of input data and/or model structure. These two are documented under “Data” and “Structure”.

Table 9: Gap analysis for modeling the residential sector in PRIMES-BuiMo

Trend cluster: Digitalization

Digitalization Smart metering Electrification of heating	Adding the feature of Smart meters will enable the implementation of electricity pricing schemes that incur behavioral changes in the electricity consumption of households (i.e. load shifting, load curtailment). This, in turn, will allow us to model load shifting of flexible appliances. New feature to be incorporated as follows: **Data**: hourly simulation of the operation of the household equipment, including heating and cooling solutions and appliances, requires as input typical load curves for certain types of equipment (those with inflexible profile, e.g., refrigeration,

	freezing, lighting, information & communication, entertainment; those with partially flexible profile, e.g., cooker, dish washer, washing machine, dryer) **Structure**: load shifting of flexible equipment
Trend cluster: Sustainable cities	
Increased urbanization	For the residential sector, PRIMES-BuiMo includes a detailed database for many building classes and explicit energy-related technologies distinguished by type and vintage. The model dynamically projects the evolution of the buildings stock through the projection of construction, demolition and renovation rates. Relatedly, the increasing urbanization trend can be modeled. **Existing feature**: buildings stock projection is model input. To be applied as follows: **Data**: adjusted buildings stock projection accounting for a modified number of building types per location - urban, semi-urban, rural reflecting urbanization trends.
Trend cluster: Green transition	
Electrification and citizen awareness in the green transition	The first part of the PRIMES-BuiMo projects useful energy demand into the future, using econometric functions which relate demand for useful energy services to macroeconomic, demographic and price variables that are exogenous projections (Fotiou et al. 2019). The useful energy categories comprise space heating, cooling, water heating, cooking, lighting, black appliances and white appliances, as well as other similar categories for the services sector. In addition, the option for the prosumagers to invest in local generation units using renewables allows tapping the potential of emissions-free energy sources. **New feature** to be incorporated as follows: **Structure**: model for local generation for covering the household needs (or part of them), while considering the possibility of bidirectional electricity flows and the coordination of several prosumagers (belonging to a certain block) by a local operator.
Trend cluster: Decentralized work	
Decentralized work	Considering the effects of working from home and thus increasing needs of useful energy demand and final energy demand, the model will incorporate the trend of decentralized work conditions. **Existing feature**: useful energy demand is input to the model. To be applied as follows: **Data**: useful energy demand to account for behavioral changes due to home office trend and policies.

Trend cluster: Climate change & behavior

Increased awareness of citizens Energy and climate policies	Here, we are considering policies incentivizing reduced energy demand. Based on that, prosumagers will reduce the useful energy demand — by improving the dwellings' energy performance through envelope renovations — and reduce the final energy demand — by investing in energy-efficient equipment, local generation and by responding to electricity price signals. **Existing feature**: useful energy demand is input to the model. To be applied as follows: **Data**: modified useful energy demand to account for behavioral changes due to policies.

Trend cluster: Socioeconomic dynamics

Energy poverty Just energy transition	Except for the detailed database for building classes and explicit energy-related technologies distinguished by type and vintage, Based on Eurostat Statistics, PRIMES-BuiMo distinguishes five income classes of households. Those affect the available income to be disposed, among others, in expenses for investing in equipment, ability to keep up with fuel purchasing expenses and capital costs for renovations. **Existing feature**: indicators for different income levels, e.g. discount rate, are model inputs. **Additional feature** to be incorporated as follows: **Data**: disposable income **Structure**: budget for investments is limited by the disposable income.

Trend cluster: Green finance

Alternative means for green finance Increasing investment expenditure in energy efficiency	Financial support schemes for prosumagers facilitate the uptake of more advanced technologies (efficient and/or climate neutral). Modelling policies incentivizing buildings renovation and the uptake of renewable energy technologies, along with socio-economic characteristics as drivers in the model, allows the increase of investment subsidies for prosuming and adjusting the perceived costs thus reflecting increased access to funding. **Existing feature**: investment subsidies, perceived costs are input to the model. To be applied as follows: **Data**: adjustments in order to account for increased access to funding, reduced perceived costs and technical uncertainties and sustainable finance developments (e.g. EU Taxonomy performance thresholds).

Trend cluster: Demographic change	
Aging population	Aging population has an impact on the rationale for selection of investments in renovation plans and choice of equipment: e.g., younger people are usually early adopters of more advanced technologies with higher investment risk. **Existing feature**: perceived cost of technologies. To be applied as follows: **Data**: perceived cost of technologies affected by demographic characteristics
Trend cluster: Great Depression II	
Reduction in disposable income	Reduced disposable income discourages households from investing in energy efficiency measures, thus reducing the potential for achieving energy savings. **New feature** to be incorporated as follows: **Data**: disposable income **Structure**: budget for investments is limited by the disposable income

4.5 Cross-sectoral Perspective

Apart from discussing the trend clusters in each sector, we also take a cross-sectoral perspective and try to summarize potential interactions among sectors, as listed in Table 10.

Table 10: Cross-sectoral impact of trends and their clusters

Trend cluster: Digitalization	
Interacting sectors: • Industry • Transport • Tertiary • Residential	Digitalization is the mega trend that is fundamentally changing all sectors, for example, flexible production in the industry, autonomous driving in the transport, online shopping in the tertiary, prosumaging behavior in the residential sector, etc. All these ICT services will increase the demand in the tertiary sector for data processing, storage, and transmission, which will drive the uptake of cloud-based services, big data and 5G. On the other hand, some sector-specific trends in digitalization also have spillover impacts. In the tertiary sector, the uptake of online shopping and food delivery increases the demand in the transport sector. In the residential sector, the transformation of households, from consumers to prosumagers, also affects the

	EV diffusion. Because with PV, the household can use the flexibility of EV batteries for a higher self-consumption rate.

Trend cluster: Decentralized Work

Interaction among sectors: • Transport • Tertiary • Residential	Decentralized work is not a totally new trend, but the Covid crisis definitely accelerated this trend. It fundamentally changes the lifestyle of people and affects the interaction and energy consumption in transport, tertiary, and residential sectors. First, the energy consumption is shifted from the tertiary to the residential sector, including the appliances, space heating and cooling, hot water, etc. Second, the volume and behavior of households' transportation demand is also changed. However, as introduced in Section 3.2.4, positive as well as negative environmental net-impacts are possible.

Trend cluster: From Owning to Sharing

Interacting sectors: • Industry • Transport • Tertiary • Residential	In general, the trend "from owning to sharing" will reduce the demand for new products in all the sectors, which further probably reduces the energy consumption in the industry and the transport sector. It would affect for example the production capacity in the industry sector, or the number of cars or the age of the car fleet in the transport sector, or devices in the tertiary sector. Apart from the savings in iron and steel production, car-sharing services also provide the households with an alternative to buying a car themselves. This might indirectly influence their incentive to adopt PV and heat pumps. Additionally, if there are policies that motivate car-sharing companies to buy electric vehicles, it will also support the electrification of the transport sector.

Trend cluster: Circular Economy

Interacting sectors: • Industry • Tertiary • Residential	Circular economy is also an overarching trend cluster that affects the interaction among sectors. For example, the recycled materials from the industry can be used for building construction in the tertiary and residential sectors and vice versa.

Trend cluster: Demographic Change

Interacting sectors: • Tertiary • Residential	In this cluster, the aging population also implies overarching impacts on multiple sectors, as well as the interaction among them, because the volume of energy consumption and behavior patterns of older people are different from the younger. In the residential sector, the aging population can lead to higher energy consumption (e.g. higher target temperature for heating in the winter), less demand for personal transport, but also

	higher demand for online shopping, food delivery, and elderly care. Furthermore, the demographic change also relates to the labor supply in the tertiary sector.

We aim to cover these interactions among sectors in the newTRENDs' scenario development, when we quantitatively analyze the impact of new trends on energy demand.

To develop consistent scenarios to model the new societal trends, we organized a modeling workshop and identified potential interaction among sectors. Two types of "interaction" were defined:

- Consistency check for the assumptions that could be aligned across models, including the framework data (e.g. population, GDP, etc.) and the model input (e.g. building stock).
- Input-output linkage, where the output of one model is used by other models as input. The "output" here can be either the result as it is, or some indicator, which can be developed, based on the results.

Based on an assessment by and a discussion between modelers, the interactions were identified as follows.

First, consistency check:

- Building stock data in FORECAST-Tertiary and INVERT.
- The assumption on "work-from-home percentage" among residential, tertiary, and transport models.
- The assumptions related to "urbanization" will be defined and consistent among residential, tertiary, and transport models.
- The assumption on "on-line shopping (due to digitalization)" among tertiary and transport models.
- The assumption on "appliance use (due to work-from-home)" among residential and tertiary models.
- The demographic assumption among residential and tertiary models. It relates the labor supply in tertiary sectors and also the "target indoor temperature" assumption in residential models.

Second, input-output linkage:

- Building (residential and tertiary) models will provide the building stock data to FORECAST-Industry for developing relevant demand.
- PRIMES-Transport will provide travel demand to tertiary and residential models.
- PRIMES-Transport will provide electricity demand of EV (in residential charging) to residential models.
- Residential (prosumager) model will provide cost saving of EV adoption for representative households (defined by number of persons, country, building type, technology adoption, etc.) to PRIMES-Transport.
- By modeling the diffusion of network-connected appliances (e.g. smart TVs, play station), FORECAST-Appliance can provide data transmission

demand for FORECAST-Tertiary. It is to be assessed if this will be actually implemented in the models.

- All sectoral models provide result to the GEM-E3 model. Furthermore, regarding circular economy in GEM-E3 and FORECAST-Industry, potential interactions are to be identified.

5. General Equilibrium Modelling

5.1 Model Introduction: GEM-E3

GEM-E3 is a large-scale multi-sectoral CGE model that since the 1990s has been extensively used by governments and public institutions to assess the socio-economic implications of policies, mostly in the domains of energy and the environment.

The development of GEM-E3 involved a series of modeling innovations that enabled its departure from the constraining framework of standard/textbook CGE models (where all resources are assumed to be fully used) to a modeling system that features a more realistic representation of the complex economic system. The key innovations include: (1) explicit representation of the financial sector, (2) semi-endogenous dynamics based on R&D-induced technical progress and knowledge spillovers, (3) the representation of multiple households (the model represents 460 households distinguished by income group), (4) unemployment in the labor market, and (5) endogenous formation of labor skills.

The model has detailed sectoral and geographical coverage, with 51 products and 46 countries/regions (global coverage) and it is calibrated to a wide range of datasets comprising of IO tables, financial accounting matrices, institutional transactions, energy balances, GHG inventories, bilateral trade matrices, investment matrices and household budget surveys. All countries in the model are linked through endogenous bilateral trade transactions identifying origin and destination. Particular focus is placed on the representation of the energy system where specialized bottom-up modules of the power generation, buildings and transport sectors have been developed.

The model is recursive-dynamic coupled with a forward-looking expectations mechanism and produces projections of the economic and energy systems until 2100 in increasing time steps: annually from 2015 to 2030 and then every five-years until 2100. The substitution elasticities of the model are not derived from the general literature but are estimated according to its dimensions and functional forms using the latest available datasets. The model is founded on rigorous and sound micro-economic theory allowing it to study in a consistent framework the inter-linkages of the economic sectors and to decompose the impacts of policies to their key driving factors. It is acknowledged that the model simulations are sensitive to a number of input parameters and modeling assumptions including capital costs of power producing technologies and associated learning rates, cost of capital and financing availability, easiness to substitute production factors, preferences over domestic and imported goods etc. To address the uncertainty within, the model provides the option to make all its parameters stochastic according to user- defined probability distributions and perform extensive sensitivity analysis.

The most important results provided by GEM-E3 are:

- full Input-Output tables for each country/region identified in the model;
- dynamic projections in constant values and deflators of national accounts by country;
- employment by economic activity and by skill and unemployment rates;
- capital, interest rates and investment by country and sector;
- private and public consumption, bilateral trade flows, consumption matrices by product and investment matrix by ownership branch;
- GHG emissions by country, sector and fuel;
- detailed energy system projections (energy demand by sector and fuel, power generation mix, deployment of transport technologies, energy efficiency improvements).

5.2 Gap Analysis and Model Improvement

In order to better represent a number of new trends and also to improve the capacity of the model to establish soft-links with sectoral models, specific model improvements are envisaged. A summary of the envisaged model improvements is presented in Table 11.

Table 11: Gap analysis for modeling the new trends in GEM-E3

Trend cluster: Socio-economic dynamics	
Socio-economic equality	Elaborate on the multiple households module. The GEM-E3 model contains 10 income classes allowing to explore socio-economic inequality.
Energy poverty	Improve the link between the households module and the consumption by purpose categories.
Trend cluster: Green finance	
Green finance	• Starting from the existing financing module further elaborate on the investment needs and financing of clean energy technologies • For the definition of the green finance we can benefit from the recent ECB publication
Trend cluster: Circular economy	
Circular economy	• Resources as a separate production factor • Exploitation of EXIOPOL/EXIOBASE to introduce resource materials in production function • Estimate circularity for specific products and update corresponding value chains • Introduce secondary market for materials • Account for rebound effects

	• Build on the recent OECD work on CGE/Circular Economies Modelling / Bohringer - Rutherford
Trend cluster: New Labor	
New labor	• Starting from the current module of endogenous capital formation we will further empirically estimate the training/education/supply decision • Introduce migration flows

5.2.1 Socio-Economic Dynamics: Multiple Households

General equilibrium models often feature one representative household over the national economy. This aggregation, although useful when large-scale modeling is required (covering many countries and for many years), may mask critical insights regarding distributional implications among household types. There exist many studies addressing this issue (Harrison et al. 2013; Rutherford and Tarr 2016; Vandyck and van Regemorter 2014), where a top down CGE has been soft-linked with a real households model (usually households are grouped by income class (quantiles or deciles) or even individually represented. Rutherford and Tarr (2008) for example have modeled 55000 households separately (Rutherford and Tarr 2008). The approach that is usually adopted, also in the GEM-E3 model, is that the national/top-down model calculates the impacts of policies on prices, aggregate disposable income and sectoral economic activity, then the prices and income are communicated to the bottom-up model where individual household demand functions are evaluated. Then aggregate preferences in the top-down model are recalibrated using the partial equilibrium individual household choices. In the process, the preferences of the real households / bottom up remain unchanged. In the newTRENDs project, the real households module of the GEM-E3 model will be further expanded so that their expenditures on energy efficiency and transport services are better aligned with their income class, preferences and consumption pattern. Link with stationary demand models (buildings) and transport models will support the calibration of the aggregate demand of households.

5.2.2 Green Finance: Energy Technologies Financing Schemes

CGE models are characterized by the representation of the real side of the economy and they do not represent money supply explicitly. Fixed quantities of resources (materials or working hours) are allocated to agents who trade at endogenously determined prices that are expressed on a numeraire. Any change in the decision of the agents is driven by changes in relative prices. The macro-economic closure of CGE models (i.e. balancing of savings investment) is a central assumption that greatly affects the adjustment of the economic system and hence the simulation properties of the model. The macroeconomic closure[5] defines what will drive investments but not necessarily, how they will be financed. The issue on investment financing in a CGE model relates to the mechanism that matches agents in surplus with agents in deficit (zero surplus on the aggregate). The assumption on keeping the supply of resources (money supply) fixed depends on the methodology adopted (neoclassical, neo Keynesian, structuralist).

In the GEM-E3 model, the inclusion of the financial sector has improved its simulation capabilities in the following respects:

1. It allows to take into account the impact of debt accumulation and debt sustainability in the ability of agents to borrow. Hence, agents with large debt-to-income ratios will not borrow at the same interest rate as the rest of the economy.
2. The model can feature alternative configurations of money supply. It can either assume fixed money supply at country level (hence any alternate financing plan needs to draw financial resources and cancel other investment projects) or fixed money supply at regional level (cross border financing) or endogenous money supply (borrowing from the future).
3. Allows for choice of alternative financing plans. The lack of financial repayment plans increases the short-term stress on financial markets and does not allow to trace the interest payments in the future (Creating payback schedules that span over many periods and countries moderates considerably the crowding out effect).
4. Allows for a detailed budgeting of debt,
5. Endogenous computation of interest rates for alternative uses of financial resources (deposits, bonds, household and business financing, etc.).

In the new newTRENDs project, the financing schemes that are expected to apply for the energy sectors will be detailed and included in the GEM-E3. This means that there will be limited financing availability and high-risk premium for fossil-based technologies and abundant low-interest financing for clean energy technologies. Interest rates will be endogenously specified and differentiated across industries and countries. The financing requirements will be derived by the bottom up/sectoral models.

5.2.3 Circular Economy: Circularity in GEM-E3

The GEM-E3 model will be developed to represent aspects of the circular economy. In its current version, GEM-E3 does not consider explicit stock-flow relationships of materials/resources (other than the fossil fuels). The objective is to develop new operational modules that will capture the economics of material circularity in a realistic, operational and detailed way, based on contributions from sectoral models. To this end, the GEM-E3 model will be developed and extended in terms of the accounting of stock/flow material

5 For a detailed description macroeconomic closures see Thisenn Zalai et al

resources (e.g. using environmentally extended input-output datasets and in its analytical capacity by introducing circularity in production processes and household consumption purposes (e.g. carpooling). The model developments will built on and go beyond existing literature. The envisaged model improvements relate to the 1) representation of secondary markets, material balances with stock vintages and flows, 2) representation of varied/multiple processes within sectors, 3) representation of heterogeneous agents behavior (e.g., capacity to adopt carpooling habits).

The extension of GEM-E3 to account for households' heterogeneity and material/flow accounting will facilitate its link with bottom-up sectoral models.

5.2.4 Labor Market: Skill Formation and R&D Performance

The GEM-E3 model has been extended to include an explicit representation of the link between human capital stock, labor productivity and the firm's capacity to absorb knowledge produced elsewhere (positive spillovers). The inclusion of human capital in the GEM-E3 model allows:

1. Labor productivities differentials across countries
2. Ensure that Human Capital is essential for the creation of knowledge (R&D, innovation, productivity growth)
3. Make the knowledge spill-overs costly (absorptive capacity)
4. The inclusion of human capital in the model also allows the endogenous representation of two basic mechanisms for sectoral output growth:
5. Increases of average productivity of workers through the acquisition of new skills or improvement of current skills
6. Increases skills availability and hence allow for capacity growth of new high value added economic activities.

The basic modeling mechanism in introducing an endogenous representation of human capital in the GEM-E3 model is to allow households and firms to endogenously decide upon the optimal schooling-education years and on the optimal workforce training respectively. The schooling decision of households (this decision regards only certain age cohorts) will allow to endogenously determine the participation rate and the supply of skills in the economy. The decision of firms to train their workers on the job will allow to model endogenous labor productivity growth through training. In this modeling approach, there is no mobility among skills, but workers of the same skill will be mobile across sectors. The households' and firms' decisions on education and training impact a human capital index which in turn is linked to: i) labor productivity, ii) the ability of a firm to generate patents and iii) the ability of replicating patents (high human stock capital will lead to easier replication of patents and increased capacity to absorb knowledge spill-overs). Thus the key model mechanisms affecting labor productivity in GEM-E3 are:

1. Household: Decision on education through utility maximization

2. Firm decision on training: The firms maximize profits and decide how much they will spend in training in order to improve the productivity of labor
3. Learning by doing: Productivity gains through repetition of working

In the newTRENDs project, the labor skill requirements by scenario will be assessed and the endogenous supply labor skill module of GEM-E3 will be activated to identify and evaluate the impact of potential skill shortages.

6. CONCLUSIONS

Developing a carbon-neutral future requires long-term strategies, and taking long-term social changes and their implications into account is essential. This is exactly what we want to assess, qualitatively discuss, and quantitatively evaluate in the newTRENDs project. The mega trends like digitalization and urbanization have overarching impacts in reshaping the whole society and energy consumption. The same holds true for other trends, for example, circular economy, prosumaging, sharing economy, which might effect some sectors more than others.

Based on a wide scanning of existing studies and a series of expert workshops, we identified the most relevant new societal trends that are unfolding. In this report, taking a sectoral perspective, we closely reviewed existing studies and discussed the impact of these trends on energy demand. Furthermore, we identified which gaps the models in the newTRENDs project have, that might hinder the modeling of the new societal trends. Based on these gaps, we propose an improvement plan for the newTRENDs project.

This report links the qualitative discussion of the trends in the sectors to model enhancements, which further support the quantitative evaluation in the next work packages. In the following work packages (WP5-7), we will improve and enhance the sectoral energy demand models and concretely integrate the new societal trends, to quantitatively analyze their impacts, as well as the macro-economic implications.

7. Bibliography

Acheampong, Ransford A.; Siiba, Alhassan (2020): Modelling the determinants of car-sharing adoption intentions among young adults: the role of attitude, perceived benefits, travel expectations and socio-demographic factors. In Transportation 47 (5), pp. 2557–2580. DOI: 10.1007/s11116-019-10029-3.

Ameli, Nadia; Brandt, Nicola (2015): What Impedes Household Investment in Energy Efficiency and Renewable Energy? In International Review of Environmental and Resource Economics 8 (1), pp. 101–138. DOI: 10.1561/101.00000067.

Anderson, James M.; Kalra, Nidhi; Stanley, Karlyn D.; Sorensen, Paul (2016): Autonomous Vehicle Technology. A Guide for Policymakers. RAND Corporation.

Banister, David (2008): The sustainable mobility paradigm. In Transport Policy 15 (2), pp. 73–80. DOI: 10.1016/j.tranpol.2007.10.005.

Bass, Frank M. (1969): A New Product Growth for Model Consumer Durables. In Management Science 15 (5), pp. 215–227. Available online at http://www.jstor.org/stable/2628128.

Beojone, Caio Vitor; Geroliminis, Nikolas (2021): On the inefficiency of ride-sourcing services towards urban congestion. In Transportation Research Part C: Emerging Technologies 124, p. 102890. DOI: 10.1016/j.trc.2020.102890.

Bertoldi, Paolo; Economidou, Marina; Palermo, Valentina; Boza-Kiss, Benigna; Todeschi, Valeria (2021): How to finance energy renovation of residential buildings: Review of current and emerging financing instruments in the EU. In WIREs Energy Environ. 10 (1). DOI: 10.1002/wene.384.

Boland, Brodie; Smet, Aaron de; Palter, Rob; Sanghvi, Aditya (2020): Reimagining the office and work life after COVID-19. McKinsey & Company. Available online at https://www.mckinsey.com/business-functions/organization/our-insights/reimagining-the-office-and-work-life-after-covid-19.

Boyacı, Burak; Zografos, Konstantinos G.; Geroliminis, Nikolas (2015): An optimization framework for the development of efficient one-way car-sharing systems. In European Journal of Operational Research 240 (3), pp. 718–733. DOI: 10.1016/j.ejor.2014.07.020.

Brugger, Heike; Eichhammer, Wolfgang; Mikova, Nadezhda; Dönitz, Ewa (2021): Energy Efficiency Vision 2050: How will new societal trends influence future energy demand in the European countries? In Energy Policy 152, p. 112216. DOI: 10.1016/j.enpol.2021.112216.

Butler, Luke; Yigitcanlar, Tan; Paz, Alexander (2021): Barriers and risks of Mobility-as-a-Service (MaaS) adoption in cities: A systematic review of the literature. In Cities 109, p. 103036. DOI: 10.1016/j.cities.2020.103036.

Campos, Inês; Marín-González, Esther (2020): People in transitions: Energy citizenship, prosumerism and social movements in Europe. In Energy Research & Social Science 69, p. 101718. DOI: 10.1016/j.erss.2020.101718.

Capros, Pantelis; Tasios, Nikolaos; Vita, Alessia de; Mantzos, Leonidas; Paroussos, Leonidas (2012): Model-based analysis of decarbonising the EU economy in the time horizon to 2050. In Energy Strategy Reviews 1 (2), pp. 76–84. DOI: 10.1016/j.esr.2012.06.003.

Cerqueira, Eugênia Dória Viana; Motte-Baumvol, Benjamin; Chevallier, Leslie Belton; Bonin, Olivier (2020): Does working from home reduce CO2 emissions? An analysis of travel patterns as dictated by workplaces. In Transportation Research Part D: Transport and Environment 83, p. 102338. DOI: 10.1016/j.trd.2020.102338.

Cheshmehzangi, Ali (2020): COVID-19 and household energy implications: what are the main impacts on energy use? In Heliyon 6 (10), e05202. DOI: 10.1016/j.heliyon.2020.e05202.

Cichosz, Marzenna; Wallenburg, Carl Marcus; Knemeyer, A. Michael (2020): Digital transformation at logistics service providers: barriers, success factors and leading practices. In The International Journal of Logistics Management 31 (2), pp. 209–238. DOI: 10.1108/IJLM-08-2019-0229.

Dannenberg, Peter; Fuchs, Martina; Riedler, Tim; Wiedemann, Cathrin (2020): Digital Transition by COVID-19 Pandemic? The German Food Online Retail. In Tijds. voor econ. en Soc. Geog. 111 (3), pp. 543–560. DOI: 10.1111/tesg.12453.

Dütschke, Elisabeth; Galvin, Ray; Brunzema, Iska (2021): Rebound and Spillovers: Prosumers in Transition. In Front Psychol 12, p. 636109. DOI: 10.3389/fpsyg.2021.636109.

Edomah, Norbert; Ndulue, Gogo (2020): Energy transition in a lockdown: An analysis of the impact of COVID-19 on changes in electricity demand in Lagos Nigeria. In Global Transitions 2, pp. 127–137. DOI: 10.1016/j.glt.2020.07.002.

Elsland, Rainer (Ed.) (2016): Long-term Energy Demand in the German Residential Sector: Nomos Verlagsgesellschaft mbH & Co. KG.

European Commission (2018): A Clean Planet for all. A European strategic long-term vision for a prosperous, modern, competitive and climate neutral economy. European Commission. Available online at https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:52018DC0773&from=EN.

European Parliament and the Council (2018): DIRECTIVE (EU) 2018/2002 OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL of 11 December 2018 amending Directive 2012/27/EU on energy efficiency. Available online at https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32018L2002&from=EN.

Eurostat (2020): Database. European Commission. Available online at https://ec.europa.eu/eurostat/data/database.

Fagnant, Daniel J.; Kockelman, Kara M. (2014): The travel and environmental implications of shared autonomous vehicles, using agent-based model scenarios. In Transportation Research Part C: Emerging Technologies 40, pp. 1–13. DOI: 10.1016/j.trc.2013.12.001.

Fallahnejad, Mostafa; Hartner, Michael; Kranzl, Lukas; Fritz, Sara (2018): Impact of distribution and transmission investment costs of district heating systems on district heating potential. In Energy Procedia 149, pp. 141–150. DOI: 10.1016/j.egypro.2018.08.178.

Fasan, René (2021): Rechenzentren in der Schweiz. Bau- und Ausbaupläne. 7pro solution AG. Available online at https://www.newsd.admin.ch/newsd/message/attachments/66087.pdf.

Felson, Marcus; Spaeth, Joe L. (1978): Community Structure and Collaborative Consumption: A Routine Activity Approach. In American Behavioral Scientist 21 (4), pp. 614–624. DOI: 10.1177/000276427802100411.

Fleiter, Tobias; Arens, Marlene; Herbst, Andrea; Rehfeldt, Matthias (2019): Industrial Innovation: Pathways to deep decarbonisation of Industry. Part 2: Scenario analysis and pathways to deep decarbonisation.

Fleiter, Tobias; Rehfeldt, Matthias; Herbst, Andrea; Elsland, Rainer; Klingler, Anna-Lena; Manz, Pia; Eidelloth, Stefan (2018): A methodology for bottom-up modelling of energy transitions in the industry sector: The FORECAST model. In Energy Strategy Reviews 22, pp. 237–254. DOI: 10.1016/j.esr.2018.09.005.

Fotiou; Vita; Capros (2019): Economic-Engineering Modelling of the Buildings Sector to Study the Transition towards Deep Decarbonization in the EU. In Energies 12 (14), p. 2745. DOI: 10.3390/en12142745.

Girod, Bastien; van Vuuren, Detlef P.; Deetman, Sebastiaan (2012): Global travel within the 2°C climate target. In Energy Policy 45, pp. 152–166. DOI: 10.1016/j.enpol.2012.02.008.

Golove, William; Eto, Joseph (1996): Market Barriers to Energy Efficiency: A Critical Reappraisal of the Rationale for Public Policies to Promote Energy Efficiency. LBNL. Berkeley.

Greenblatt, Jeffery B.; Saxena, Samveg (2015): Autonomous taxis could greatly reduce greenhouse-gas emissions of US light-duty vehicles. In Nature Climate Change 5 (9), pp. 860–863. DOI: 10.1038/nclimate2685.

Greenblatt, Jeffery B.; Shaheen, Susan (2015): Automated Vehicles, On-Demand Mobility, and Environmental Impacts. In Current Sustainable/Renewable Energy Reports 2 (3), pp. 74–81. DOI: 10.1007/s40518-015-0038-5.

Gurumurthy, Krishna Murthy; Kockelman, Kara M. (2018): Analyzing the dynamic ride-sharing potential for shared autonomous vehicle fleets using cellphone data from Orlando, Florida. In Computers, Environment and Urban Systems 71, pp. 177–185. DOI: 10.1016/j.compenvurbsys.2018.05.008.

Han, Changwoo; Hong, Yun-Chul (2020): Decrease in Ambient Fine Particulate Matter during COVID-19 Crisis and Corresponding Health Benefits in Seoul, Korea. In IJERPH 17 (15), p. 5279. DOI: 10.3390/ijerph17155279.

Harrison, Glenn W.; Rutherford, Thomas F.; Tarr, David G. (2013): Trade liberalization, poverty and efficient equity. In: Applied Trade Policy Modeling in 16 Countries, Volume 34: WORLD SCIENTIFIC (World Scientific Studies in International Economics, Volume 34), pp. 255–286.

Hartner, M.; Forthuber, S.; Kranzl, L.; Fritz, S.; Aichinger, E.; Müller, A. et al. (2019): D.5.8: WP5 Summary Report - Energy Systems: Demand perspective. A report compiled within the H2020 project SET-Nav. Wien: Technische Universität Wien.

Heinen, Steve; Burke, Daniel; O'Malley, Mark (2016): Electricity, gas, heat integration via residential hybrid heating technologies – An investment model assessment. In Energy 109, pp. 906–919. DOI: 10.1016/j.energy.2016.04.126.

Herbst, A. (2017): Kopplung eines makroökonomischen Modells mit einem »bottom-up« Energienachfrage-Modell für die Industrie. Eine Fallstudie über die Stahlindustrie. Dissertation. Zentrale Hochschulbibliothek Flensburg, Flensburg.

Herbst, A.; Fleiter, T.; Jochem, E. (2014): Modelling recycling and material efficiency trends in the European steel industry. European Council for an Energy-Efficient Economy. ECEEE 2014 Industrial Summer Study on Energy Efficiency (Retool for a competitive and sustainable industry).

Herbst, A.; Fleiter, T.; Rehfeldt, M. (Eds.) (2018): Scenario analysis of a low-carbon transition of the EU industry by 2050: Extending the scope of mitigation options. ECEEE Industrial Summer Study on Energy Efficiency. Panel: 4. Technology, products and system optimisation.

Herbst, A.; Zanoni, S. (2020): Introduction to Panel 2: Sustainable production towards a circular economy. ECEEE Industrial Summer Study.

Hertwich, E. G.; Lifset, R.; Pauliuk, S.; Heeren, N.; Ali, S.; Tu, Q. et al. (2020): Resource Efficiency and Climate Change: Material Efficiency Strategies for a Low-Carbon Future.

Ho, Chinh Q.; Hensher, David A.; Mulley, Corinne; Wong, Yale Z. (2018): Potential uptake and willingness-to-pay for Mobility as a Service (MaaS): A stated choice study. In Transportation Research Part A: Policy and Practice 117, pp. 302–318. DOI: 10.1016/j.tra.2018.08.025.

Horne, Matt; Jaccard, Mark; Tiedemann, Ken (2005): Improving behavioral realism in hybrid energy-economy models using discrete choice studies of personal transportation decisions. In Energy Economics 27 (1), pp. 59–77. DOI: 10.1016/j.eneco.2004.11.003.

Horsky, Dan (1990): A Diffusion Model Incorporating Product Benefits, Price, Income and Information. In Marketing Science 9 (4), pp. 342–365. Available online at http://www.jstor.org/stable/184000.

Hossain, Md. Uzzal; Ng, S. Thomas (2018): Critical consideration of buildings' environmental impact assessment towards adoption of circular economy: An analytical review. In Journal of Cleaner Production 205, pp. 763–780. DOI: 10.1016/j.jclepro.2018.09.120.

Iacobucci, Riccardo; McLellan, Benjamin; Tezuka, Tetsuo (2018): Modeling shared autonomous electric vehicles: Potential for transport and power grid integration. In Energy 158, pp. 148–163. DOI: 10.1016/j.energy.2018.06.024.

IEA (2019): Material efficiency in clean energy transitions. Available online at www.iea.org/reports/material-efficiency-in-clean-energy-transition.

IEA (2020): Appliances and Equipment. International Energy Agency. Paris. Available online at https://www.iea.org/reports/appliances-and-equipment.

Invert/EE-Lab. Modelling the energy demand for space heating and cooling in building stocks (2020). Available online at https://invert.at/, updated on 5/29/2020, checked on 5/29/2020.

IPCC (2014): Climate Change 2014–Impacts, Adaptation and Vulnerability: Regional Aspects. Cambridge University Press.

Jakob, Martin; Müller, Jonas; Altenburger, Adrian (2021): Rechenzentren in der Schweiz. Stromverbrauch und Effizienzpotenzial. TEP Energy; Hochschule Luzern. Available online at https://www.newsd.admin.ch/newsd/message/attachments/66076.pdf.

Kandler, Christian (2017): Modellierung von Zeitnutzungs-, Mobilitäts- und Energieprofilen zur Bestimmung der Potentiale von Energiemanagementsystemen in Haushalten. Dissertation. Technischen Universität München, München. Available online at https://mediatum.ub.tum.de/doc/1339276/file.pdf.

Karplus, Valerie J.; Paltsev, Sergey; Babiker, Mustafa; Reilly, John M. (2013): Applying engineering and fleet detail to represent passenger vehicle transport in a computable general equilibrium model. In Economic Modelling 30, pp. 295–305. DOI: 10.1016/j.econmod.2012.08.019.

Kim, Heetae; Choi, Kyu Ha; Kim, Ki Joon; Park, Eunil (2017): From owning to sharing: understanding the emergence of social sharing services. In Program 51 (2), pp. 102–115. DOI: 10.1108/PROG-02-2016-0010.

Kranzl, Lukas; Aichinger, Eric; Büchele, Richard; Forthuber, Sebastian; Hartner, Michael; Müller, Andreas; Toleikyte, Agne (2019): Are scenarios of energy demand in the building stock in line with Paris targets? In Energy Efficiency 12 (1), pp. 225–243. DOI: 10.1007/s12053-018-9701-1.

Kranzl, Lukas; Hummel, Marcus; Müller, Andreas; Steinbach, Jan (2013): Renewable heating: Perspectives and the impact of policy instruments. In Energy Policy 59, pp. 44–58. DOI: 10.1016/j.enpol.2013.03.050.

Lachapelle, Ugo; Tanguay, Georges A.; Neumark-Gaudet, Léa (2018): Telecommuting and sustainable travel: Reduction of overall travel time, increases in non-motorised travel and congestion relief? In Urban Studies 55 (10), pp. 2226–2244. DOI: 10.1177/0042098017708985.

Le Den, X.; Porteron, S.; Collin, C.; Hvid Horup Sorensen, L.; Herbst, A.; Rehfeldt, M. et al. (2020a): Quantification methodology for, and analysis of, the decarbonisation benefits of sectoral circular economy actions.

LeDen et al. (2020b): The decarbonisation benefist of sectoral circular economy actions. Final Report for the European Environmental Agency.

Li, Francis; Trutnevyte, Evelina; Strachan, Neil (2015): A review of socio-technical energy transition (STET) models. In Technological Forecasting and Social Change 100, pp. 290–305. DOI: 10.1016/j.techfore.2015.07.017.

Lim, Hazel; Taeihagh, Araz (2018): Autonomous Vehicles for Smart and Sustainable Cities: An In-Depth Exploration of Privacy and Cybersecurity Implications. In Energies 11 (5), p. 1062. DOI: 10.3390/en11051062.

Lund, S.; Madgavkar, A.; Manyika, J.; Smit, S. (2020): What's next for remote work: An analysis of 2,000 tasks, 800 jobs, and nine countries. Mckinsey & Company. Available online at https://www.mckinsey.com/featured-insights/future-of-work/whats-next-for-remote-work-an-analysis-of-2000-tasks-800-jobs-and-nine-countries.

Lyons, L. (2019): Digitalisation: opportunities for heating and cooling: Publications Office.

Mahajan, Vijay; Peterson, Robert A. (2010): Models for innovation diffusion. [Nachdr.]. Newbury Park, Calif.: Sage (Sage University Paper Series. Quantitative applications in the social sciences, 48).

Mancarella, Pierluigi (2014): MES (multi-energy systems): An overview of concepts and evaluation models. In Energy 65, pp. 1–17. DOI: 10.1016/j.energy.2013.10.041.

Masanet, Eric; Shehabi, Arman; Lei, Nuoa; Smith, Sarah; Koomey, Jonathan (2020): Recalibrating global data center energy-use estimates. In Science 367 (6481), pp. 984–986. DOI: 10.1126/science.aba3758.

Material Economics (2018): The Circular Economy. a Powerful Force for Climate Mitigation. Stockholm.

Mathew, Jijo K.; Liu, Mingmin; Seeder, Sonya; Li, Howell; Bullock, Darcy M. (2019): Analysis of E-Scooter Trips and Their Temporal Usage Patterns. In ITE journal 89 (6). Available online at https://www.proquest.com/openview/5ab28c4cc69276538d1b258929dab414/1?cbl=42116&pq-origsite=gscholar.

McCollum, David; Krey, Volker; Kolp, Peter; Nagai, Yu; Riahi, Keywan (2014): Transport electrification: A key element for energy system transformation and climate stabilization. In Climatic Change 123 (3), pp. 651–664. DOI: 10.1007/s10584-013-0969-z.

McKibbin, Warwick J.; Fernando, Roshen (2020): The Global Macroeconomic Impacts of COVID-19: Seven Scenarios. In SSRN Journal. DOI: 10.2139/ssrn.3547729.

Mikulić, Davor; Bakarić, Ivana Rašić; Slijepčević, Sunčana (2016): The economic impact of energy saving retrofits of residential and public buildings in Croatia. In Energy Policy 96, pp. 630–644. DOI: 10.1016/j.enpol.2016.06.040.

Milasi, S.; Fernandez-Macias, E.; Gonzalez-Vasquez, I. (2020): Telework in the EU before and after the COVID-19: where we were, where we head to. Available online at https://ec.europa.eu/jrc/sites/default/files/jrc120945_policy_brief_-_covid_and_telework_final.pdf.

Montevecchi, F.; Stickler, T.; Hintemann, R.; Hinterholzer, S. (2020): Energy-efficient Cloud Computing Technologies and Policies for an Eco-friendly Cloud Market. Final Study Report. European Commission. Vienna. Available online at https://digital-strategy.ec.europa.eu/en/library/energy-efficient-cloud-computing-technologies-and-policies-eco-friendly-cloud-market.

Müller, A. (2015): Energy Demand Assessment for Space Conditioning and Domestic Hot Water: A Case Study for the Austrian Building Stock. Technische Universität Wien, Wien, Austria. Available online at https://www.invert.at/Dateien/Dissertation_AndreasM.pdf.

Müller, A.; Kranzl, L.; Hartner, M.; Brugger, H.; Durand, A.; Schlomann, B. et al. (2018): Discussion paper on the definition of scenarios. Report in the frame of the project CHEETAH.

Müller, Andreas; Hummel, Marcus; Kranzl, Lukas; Fallahnejad, Mostafa; Büchele, Richard (2019): Open Source Data for Gross Floor Area and Heat Demand Density on the Hectare Level for EU 28. In Energies 12 (24), p. 4789. DOI: 10.3390/en12244789.

Müller, J.; Jakob, M.; Altenburger, A. (Eds.) (2021): Power consumption and energy efficiency potentials in data centers: case study Switzerland. Proceeding ECEEE.

Nelson, John D.; Wright, Steve; Masson, Brian; Ambrosino, Giorgio; Naniopoulos, Aristotelis (2010): Recent developments in Flexible Transport Services. In Research in Transportation Economics 29 (1), pp. 243–248. DOI: 10.1016/j.retrec.2010.07.030.

Nishino, Nariaki; Takenaka, Takeshi; Takahashi, Hiroki (2017): Manufacturer's strategy in a sharing economy. In CIRP Annals 66 (1), pp. 409–412. DOI: 10.1016/j.cirp.2017.04.004.

Noussan, Michel; Tagliapietra, Simone (2020): The effect of digitalization in the energy consumption of passenger transport: An analysis of future scenarios for Europe. In Journal of Cleaner Production 258, p. 120926. DOI: 10.1016/j.jclepro.2020.120926.

O'Brien, William; Yazdani Aliabadi, Fereshteh (2020): Does telecommuting save energy? A critical review of quantitative studies and their research methods. In Energy and Buildings 225, p. 110298. DOI: 10.1016/j.enbuild.2020.110298.

Ogryzek, Marek; Adamska-Kmieć, Daria; Klimach, Anna (2020): Sustainable Transport: An Efficient Transportation Network—Case Study. In Sustainability 12 (19), p. 8274. DOI: 10.3390/su12198274.

Ouyang, Danhua; Zhou, Shen; Ou, Xunmin (2021): The total cost of electric vehicle ownership: A consumer-oriented study of China's post-subsidy era. In Energy Policy 149, p. 112023. DOI: 10.1016/j.enpol.2020.112023.

Paddeu, Daniela; Shergold, Ian; Parkhurst, Graham (2020): The social perspective on policy towards local shared autonomous vehicle services (LSAVS). In Transport Policy 98, pp. 116–126. DOI: 10.1016/j.tranpol.2020.05.013.

Paiho, Satu; Ahvenniemi, Hannele (2017): Non-Technical Barriers to Energy Efficient Renovation of Residential Buildings and Potential Policy Instruments to overcome Them—Evidence from Young Russian Adults. In Buildings 7 (4), p. 101. DOI: 10.3390/buildings7040101.

Palm, Jenny; Reindl, Katharina (2018): Understanding barriers to energy-efficiency renovations of multifamily dwellings. In Energy Efficiency 11 (1), pp. 53–65. DOI: 10.1007/s12053-017-9549-9.

Paschou, T.; Rapaccini, M.; Adrodegari, F.; Saccani, N. (2020): Digital servitization in manufacturing: A systematic literature review and research agenda. In Industrial Marketing Management 89, pp. 278–292. DOI: 10.1016/j.indmarman.2020.02.012.

Pauliuk, Stefan; Heeren, Niko (2021): Material efficiency and its contribution to climate change mitigation in Germany: A deep decarbonisation scenario analysis until 2060. In Journal of Industrial Ecology 25 (2), pp. 479–493. DOI: 10.1111/jiec.13091.

Pauliuk, Stefan; Heeren, Niko; Berrill, Peter; Fishman, Tomer; Nistad, Andrea; Tu, Qingshi et al. (2021): Global scenarios of resource and emission savings from material efficiency in residential buildings and cars. In Nature Communications 12 (1), p. 5097. DOI: 10.1038/s41467-021-25300-4.

Paulou, J.; Lonsdale, J.; Jamieson, M.; Neuweg, I.; Trucco, P.; Maio, P.; Warringa, G. (2014): Financing the energy renovation of buildings with cohesion policy funding. Technical Guidance. European Comission DG Energy.

Qarnain, Syed Shuibul; Sattanathan, Muthuvel; Sankaranarayanan, Bathrinath; Ali, Syed Mithun (2020): Analyzing energy consumption factors during coronavirus (COVID-19) pandemic outbreak: a case study of residential society. In Energy Sources, Part A: Recovery, Utilization, and Environmental Effects, pp. 1–20. DOI: 10.1080/15567036.2020.1859651.

Rehfeldt, M.; Herbst, A.; Porteron, S. (2020): Modelling circular economy action impacts in the building sector on the EU cement industry.

Reul, Julian; Grube, Thomas; Stolten, Detlef (2021): Urban transportation at an inflection point: An analysis of potential influencing factors. In Transportation Research Part D: Transport and Environment 92, p. 102733. DOI: 10.1016/j.trd.2021.102733.

Rothballer, C. (2018): Discussion on EED policy recommendations with national experts. Concerted Action on the Energy Efficiency Directive, 2018.

Rotman, David (2020): We're Not Prepared for the End of Moore's Law. MIT Technology Review. Available online at https://www.technologyreview.com/2020/02/24/905789/were-not-prepared-for-the-end-of-moores-law/.

Rutherford, Thomas F.; Tarr, David G. (2008): Poverty effects of Russia's WTO accession: Modeling “real” households with endogenous productivity effects. In Journal of International Economics 75 (1), pp. 131–150. DOI: 10.1016/j.jinteco.2007.09.004.

Rutherford, Thomas F.; Tarr, David G. (2016): Trade liberalization, product variety and growth in a small open economy: a quantitative assessment. In : Trade Policies for Development and Transition, Volume 57: WORLD SCIENTIFIC (World Scientific Studies in International Economics, Volume 57), pp. 389–414.

Saheb, Y.; Bódis, K.; Szabó, S.; Ossenbrink, H.; Panev, S. (2015): Energy Renovation: The Trump Card for the New Start for Europe. European Commission. Joint Research Centre.

Said, Maher; Biehl, Alec; Stathopoulos, Amanda (2021): Interdependence in active mobility adoption: Joint modelling and motivational spillover in walking, cycling and bike-sharing. In International Journal of Sustainable Transportation, pp. 1–19. DOI: 10.1080/15568318.2021.1885769.

Samek Lodovici, Manuela; Ferrari, Elena; Paladino, Emma; Pesce, Flavia; Frecassetti, Pietro; Aram, Eliat; Hadjvassiliou, Kari (2021): The impact of teleworking and digital work on workers and society. EMPL committee. Available online at https://www.europarl.europa.eu/RegData/etudes/STUD/2021/662904/IPOL_STU(2021)662904_EN.pdf.

Scorrano, Mariangela; Danielis, Romeo (2021): The characteristics of the demand for electric scooters in Italy: An exploratory study. In Research in Transportation Business & Management 39, p. 100589. DOI: 10.1016/j.rtbm.2020.100589.

Sell, R.; Rassõlkin, A.; Wang, R.; Otto, T. (2019): Integration of autonomous vehicles and Industry 4.0. In Proc. Estonian Acad. Sci. 68 (4), p. 389. DOI: 10.3176/proc.2019.4.07.

Shaheen, Susan; Chan, Nelson (2015): Mobility and the Sharing Economy: Impacts Synopsis. University of California, Berkeley. Available online at http://innovativemobility.org/wp-content/uploads/2015/07/Innovative-Mobility-Industry-Outlook_SM-Spring-2015.pdf.

Shanks, W.; Dunant, C. F.; Drewniok, Michał P.; Lupton, R. C.; Serrenho, A.; Allwood, Julian M. (2019): How much cement can we do without? Lessons from cement material flows in the UK. In Resources, Conservation and Recycling 141, pp. 441–454. DOI: 10.1016/j.resconrec.2018.11.002.

Shibayama, Takeru; Sandholzer, Fabian; Laa, Barbara; Brezina, Tadej (2021): Impact of COVID-19 lockdown on commuting. 70-93 Pages / European Journal of Transport and Infrastructure Research, Vol. 21 No. 1 (2021). DOI: 10.18757/EJTIR.2021.21.1.5135.

Shnapp, S.; Paci, D.; Bertoldi, P. (2020): Untapping multiple benefits: hidden values in environmental and building policies. European Union. Available online at https://publications.jrc.ec.europa.eu/repository/bitstream/JRC120683/untapping_multiple_benefits_-_hidden_values_in_environmental_and_building_policies.pdf.

Shokouhyar, Sajjad; Shokoohyar, Sina; Sobhani, Anae; Gorizi, Amirsalar Jafari (2021): Shared mobility in post-COVID era: New challenges and opportunities. In Sustainable Cities and Society 67, p. 102714. DOI: 10.1016/j.scs.2021.102714.

Sioshansi, Fereidoon; Webb, Jeremy (2019): Transitioning from conventional to electric vehicles: The effect of cost and environmental drivers on peak oil demand. In Economic Analysis and Policy 61, pp. 7–15. DOI: 10.1016/j.eap.2018.12.005.

Siskos, Pelopidas; Zazias, Georgios; Petropoulos, Apostolos; Evangelopoulou, Stavroula; Capros, Pantelis (2018): Implications of delaying transport decarbonisation in the EU: A systems analysis using the PRIMES model. In Energy Policy 121, pp. 48–60. DOI: 10.1016/j.enpol.2018.06.016.

Statharas, Stergios; Moysoglou, Yannis; Siskos, Pelopidas; Zazias, Georgios; Capros, Pantelis (2019): Factors Influencing Electric Vehicle Penetration in the EU by 2030: A Model-Based Policy Assessment. In Energies 12 (14), p. 2739. DOI: 10.3390/en12142739.

Strulak-Wójcikiewicz, Roma; Lemke, Justyna (2019): Concept of a Simulation Model for Assessing the Sustainable Development of Urban Transport. In Transportation Research Procedia 39, pp. 502–513. DOI: 10.1016/j.trpro.2019.06.052.

Train, Kenneth E. (2012): Discrete Choice Methods with Simulation. Second edition. Cambridge: Cambridge University Press.

Tronvoll, Bård; Sklyar, Alexey; Sörhammar, David; Kowalkowski, Christian (2020): Transformational shifts through digital servitization. In Industrial Marketing Management 89, pp. 293–305. DOI: 10.1016/j.indmarman.2020.02.005.

UN (2017): World Population Prospects. United Nations. Available online at https://population.un.org/wpp/Download/Standard/Population/.

United Nations Environment Programme (2020): The 2020 Global Status Report for Buildings and Construction: Towards a Zero-emission, Efficient and Resilient Buildings and Construction Sector. Available online at https://globalabc.org/sites/default/files/inline-files/2020%20Buildings%20GSR_FULL%20REPORT.pdf.

Valentová, Michaela (2010): Barriers to Energy Efficiency – Focus on Transaction Costs. In Acta Polytech 50 (4). DOI: 10.14311/1247.

van Lier, Tom; Witte, Astrid de; Macharis, Cathy (2014): How worthwhile is teleworking from a sustainable mobility perspective? The case of Brussels Capital region. European Journal of Transport and Infrastructure Research, Vol 14 No 3 (2014). DOI: 10.18757/EJTIR.2014.14.3.3033.

Vandyck, Toon; van Regemorter, Denise (2014): Distributional and regional economic impact of energy taxes in Belgium. In Energy Policy 72, pp. 190–203. DOI: 10.1016/j.enpol.2014.04.004.

Wright, Steve; Emele, C. David; Fukumoto, Masayuki; Velaga, Nagendra R.; Nelson, John D. (2014): The design, management and operation of flexible transport systems: Comparison of experience between UK, Japan and India. In Research in Transportation Economics 48, pp. 330–338. DOI: 10.1016/j.retrec.2014.09.060.

Zhang, Qi; Li, Hailong; Zhu, Lijing; Campana, Pietro Elia; Lu, Huihui; Wallin, Fredrik; Sun, Qie (2018): Factors influencing the economics of public charging infrastructures for EV – A review. In Renewable and Sustainable Energy Reviews 94, pp. 500–509. DOI: 10.1016/j.rser.2018.06.022.

Zhang, Runsen; Fujimori, Shinichiro (2020): The role of transport electrification in global climate change mitigation scenarios. In Environ. Res. Lett. 15 (3), p. 34019. DOI: 10.1088/1748-9326/ab6658.

Zhou, Kaile; Yang, Shanlin (2016): Understanding household energy consumption behavior: The contribution of energy big data analytics. In Renewable and Sustainable Energy Reviews 56, pp. 810–819. DOI: 10.1016/j.rser.2015.12.001.

A.1 APPENDIX: MODEL INTRODUCTION

A.1.1 FORECAST-Industry

FORECAST is a bottom-up energy demand model. It maps the technology structure of industry and calculates energy consumption and emissions as well as costs at the process level. Input data for the modeling are overarching activity variables such as economic performance per sector, energy and CO_2 prices, assumptions on instruments, structural data such as energy and GHG balances as well as techno-economic data of the mapped technologies. For parameterization, we use statistical data, empirical studies, literature and expert estimates. An overarching model description is available in Fleiter et al. (2018).

Technology areas. The structure of the model is based, on the one hand, on the structure of the industrial sector, whereby areas that are as homogeneous as possible are grouped together, and, on the other hand, on the availability of data.

The model is calibrated and ready for use for **EU-wide calculations**. FORECAST currently covers all countries of the EU27 (plus the United Kingdom, Norway and Switzerland) and has a distinctive and regularly updated database for them. It is compatible with both the German (AGEB) and the Eurostat energy balances. The methodological approach (representation of industry at process level) allows country-specific features of the industrial structure to be mapped.

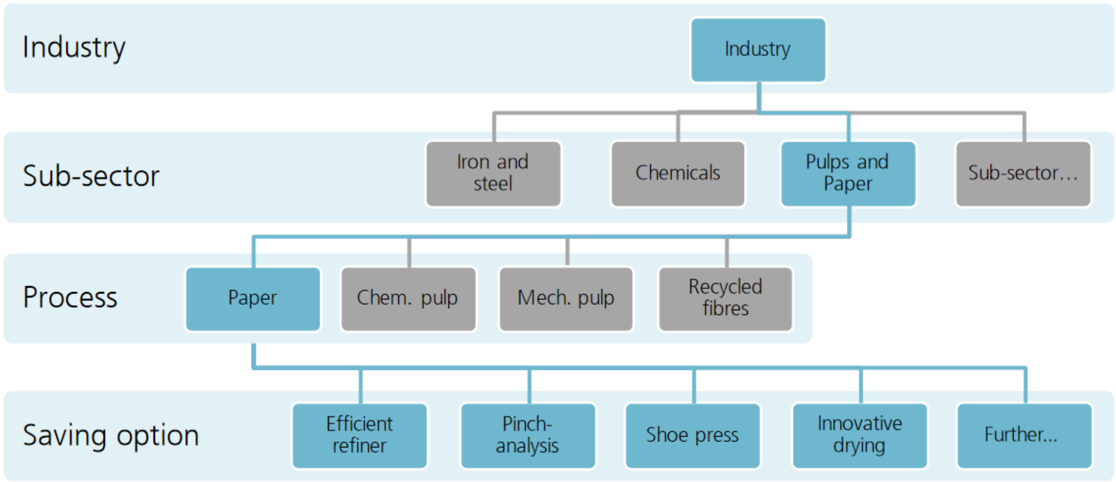
Simulation of technology diffusion and investment decisions. FORECAST Industry places particular emphasis on modeling transformation pathways with a high degree of technological detail. For example, steam generation is modeled with a stock model. This makes it possible to model the inertia of the reaction to price signals on the basis of the age structure of the existing plants, the replacement rate linked to the technical lifetime of the plants and (abstracted) assumptions on market properties (e.g. the transparency of the market). Especially in the context of limited time horizons, windows of opportunity for technology exchange can be described in this way. In addition, plants/facilities of the energy-intensive industry are of considerable importance (e.g. blast furnaces, steam-cracking furnaces, paper machines). These are recorded individually at site level and with their age structure. The time restrictions associated with the decarbonization of the industries (infrastructure, price signals, modernization cycles...) can thus be taken into account in detail. Different options are compared within the framework of the scenario technique.

Model database. FORECAST Industry uses a variety of different data sources, which are structured and bundled in a model database. Relevant, annually updated data include energy balances (AGEB, Eurostat), production quantities (various sources, associations, national/European statistics) and emission quantities (EU ETS, national inventory reports, CRF tables). In addition, there are techno-economic data on the processes, process heat generation technologies and innovative technology options (CCU/S, H2-DRI, new cement types...) and economic data (energy carrier prices, CO2 prices). Furthermore, an EU-wide database of basic industry sites is connected to the model (Manz et al. 2018).

Simulation of policy instruments. FORECAST Industry allows interventions in the simulated process at many points in the modeling. These are used to integrate policy measures, including price signals and regulatory measures as well as more soft levers (e.g. access to information). The degree of abstraction varies greatly, depending on the availability of empirical data. Behavioral aspects play a role at various points, especially when the reaction to price signals is assessed. The EU ETS as the central instrument of the EU's decarbonization efforts is mapped at process or sub-sector level (corresponding to ETS activities). Accordingly, fuel requirements, which are not represented in the EU ETS, are assigned to national pricing systems.

Model structure: sub-sectors and processes. FORECAST is structured hierarchically and divides industry into individual economic sectors or sub-sectors based on energy balances. These are assigned to processes, which are described by a specific energy consumption and an activity variable. The model is based on a bottom-up quantity structure for calculating the energy demand of the processes and the space heating demand. At the process level, the absolute energy demand per process is calculated as bottom-up energy consumption via the physical production (in tons) per process and its specific energy consumption. The space heating demand is calculated via characteristic values for the energy demand per m² area per sub-sector. For the simulation of the energy consumption development, the residual value from the determined bottom-up energy consumption per sub-sector is compared with the energy demand per sub-sector shown in the energy balances. The residual value is updated using the gross value added of the sub-sector. The downstream modules (electric motors, furnaces, steam systems) are based on the extrapolation of these two bottom-up modules.

Figure A.1-1: Hierarchical structure of the FORECAST sub-module for energy-intensive processes



Source: FORECAST

Definition of sub-sectors. For the Eurostat energy balances, the industry structure comprises the eight separate industries of Section C "Manufacturing" of the NACE 2 classification.

Table A.1-1: Sub-sector-structure FORECAST (Eurostat)

Name	NACE 2 Category
Iron and steel	24.1, 24.2, 24.3, 24.51, 24.52
Non-ferrous metals	24,4, 24.53, 24.54
Pulp and paper	17, 18
Non-metallic minerals	23
Chemicals	20
Food, drink, tobacco	10, 11, 12
Engineering	25, 26, 27, 28, 29, 30
Other	Remaining manufacturing (C)

Source: FORCAST (Fraunhofer ISI)

For process-specific technologies, the main driver is the projection of physical production (e.g. tons of crude steel from blast furnaces). The 70 most energy- and green-house-gas-intensive processes are considered separately in the model. For each of these processes, the specific energy consumption/GHG emissions, temperature ranges and the physical production output per country are important modeling parameters. Depending on the data availability, processes can consist of small individual production steps (e.g. burning of clinker in the cement industry) or entire production lines for individual products or product groups (e.g. production of paper). In total, FORECAST currently considers more than 70 individual processes as listed in Figure A. 1-2 allowing for a huge level of detail.

Figure A.1-2: Overview of products covered in FORECAST-Industry for bottom-up calculation by sub-sector

Non-metallic minerals	Chemicals	Non-ferrous metals	Iron and steel
Container glass	Adipic acid	Aluminium, primary	Sinter
Flat glass	Ammonia	Aluminium, secondary	Oxygen steel
Fibre glass	Calcium carbide	Aluminium extruding	Electric steel
Other glass	Carbon black	Aluminium foundries	Rolled steel
Houseware, sanitary ware	Chlorine, diaphragma	Aluminium rolling	Coke oven coke
Technical, other ceramics	Chlorine, membrane	Copper, primary	Smelting reduction
Tiles, plates, refractories	Chlorine, mercury	Copper, secondary	Direct reduction
Clinker Calcination-Dry	Ethylene	Copper further treatment	DR H2 plasma steel
Clinker Calcination-Semidry	Methanol	Zinc, primary	DR RES electrolysis steel
Clinker Calcination-Wet	Nitric acid	Zinc, secondary	
Preparation of limestone	Oxygen		
Gypsum	Polycarbonates		
Cement grinding	Polyethylene		
Lime milling	Polypropylene		
Bricks	Polysulfones		
Lime burning	Soda ash		
RES electric melting	TDI		
Less carbon cement (30%)	Titanium dioxide		
Low carbon cement (50%)	RES H2 Ammonia		
Low carbon cement (70%)	RES H2 Methanol		
Petrochemicals	**Food drink and tobacco**	**Pulp and paper**	**Others**
Refinery type 1	Sugar	Paper	Plastics: Extrusion
Refinery type 2	Dairy	Chemical pulp	Plastics: Injection moulding
Refinery type 3	Brewing	Mechanical pulp	Plastics: Blow moulding
Refinery type 4	Meat processing	Recovered fibres	
	Bread & bakery		
	Starch		

Source: FORECAST

The production data for the individual processes is collected by country and is regarded as the backbone of the FORECAST model. While no individual data source is available that provides data for all products, production data is collected from a variety of sources as shown in Figure A1.3.

Figure A.1-3: Main data sources for historic production data of processes by country

Sub-sector / process	Data source	Completeness/quality of data
Iron and steel	World Steel Association	Very complete
Cement	Cembureau, Odyssee	Very complete
Glass	Glassglobal	Complete, but calculated based on capacity and utilisation by country
Pulp and paper	German Pulp and Paper Association (VDP), FAO Stat	Very complete
Aluminium and copper	US Geological survey	Complete for primary and secondary aluminium, less so for further treatment
Chemicals: Ammonia	UNFCCC	Complete, but some uncertainty
Chemicals: Ethylene	UNFCCC	Complete, but some uncertainty
Chemicals: Oxygen	Eurostat	Complete, but some uncertainty and data for some small countries missing
Chemicals: Methanol	UNFCCC	Many gaps
Chemicals: Polyethylene	UN Commodity Production Database	Some uncertainty
Food, drink and tobacco	Mainly UN Commodity Production Database, UN Data, German brewery association	Several gaps

A.1.2 PRIMES-TREMOVE

A.1.2.1 Model Introduction

Energy consumption for transportation purposes generates very significant amount of greenhouse gases and emission abatement is particularly inelastic in this sector. Transport is by far the largest consumer of oil products. Expenditures for transportation purposes represent a significant percentage of GDP.

Because of its importance, PRIMES devotes particular focus on transport and includes very detailed modeling which covers the energy and mobility nexus and also can handle a large variety of policy measures addressing the transport sector.

PRIMES-TREMOVE Transport sub-model produces projections of transport activity, stock turnover of transport means, technology choice, energy consumption by fuel and emissions and other externalities. PRIMES-TREMOVE is a very detailed partial equilibrium simulation tool that can be used for scenario projections and impact analysis of policies in the transport sector. The model has been designed with focus on long-term simulation of conditions which would drive restructuring of the sector towards new, cleaner and more efficient transportation technologies and fuels. For this purpose, the transport model fully handles possible electrification of road transport, high blending of bio-fuels in all transport sectors and market penetration of alternative fuels including hydrogen. The simulation of dynamics of changes combines modeling of consumer choices, technology change, refueling and recharging infrastructure and policy instruments which are meant to enable the changes.

A.1.2.2 Model Overview

PRIMES-TREMOVE Transport Model produces projections covering the entire transport sector by 5-year steps up to 2050. The model projects mobility for passengers and freight, allocation of mobility by transport mode, projection of mobility by type of trip, allocation of mobility by mode in transport means, investment and scrapping of transport means, energy consumption and emissions of transport means and costs and prices of transport. Choices among alternative options and investment are simulated by agent which are considered to be representative of classes of transport consumers. The choices are based on economics and utility from mobility and also depend on policies, technology availability and infrastructure. The projection includes details for a large number of transport means technologies and fuels, including conventional and alternative types, and their penetration in various transport market segments. The projection also includes details about greenhouse gas and air pollution emissions, as well as impacts on externalities such as noise and accidents. Operation costs, investment costs, external costs, tax revenues or subsidy costs, congestion indirect costs and others are included in the model reports.

Agent choices are derived from structural microeconomic optimization, in which technology features and transport activity allocation possibilities are embedded.

The model can run either as a standalone tool or fully integrated in the rest of the PRIMES energy systems model. In the integrated run mode, the transport model takes from the rest of PRIMES projection of prices for fuels, biofuels, electricity and hydrogen, as well as carbon prices where applicable. The transport model transmits projection of fuel, electricity and hydrogen consumption to the rest of PRIMES model. The model linkage is also used for life cycle analysis of emissions of fuels used in transport, covering the entire well to wheel calculations. The possibilities, costs and prices of biofuel supply are assessed using the dedicated PRIMES-Biomass Supply Model which is also linked with the core PRIMES model and the transport model, taking from them demand figures and conveying to them bio-energy commodity prices. So lifecycle analysis of emissions and energy is performed for all fuel types including alternative fuels.

PRIMES-TREMOVE Transport model can also link with TRANSTOOLS, a network transport model with spatial information. The module handles transformation of

TRANSTOOLS mobility projections in transport activity variables handled by PRIMES.

A.1.2.3 Policy Analysis Focus

PRIMES-TREMOVE Transport model includes a large variety of policy measures which can be mirrored in scenarios. Policy targets, for example on future emissions in transport, can be forced in scenario projections. The model endogenously determines drivers which influence restructuring in transport and substitutions enabling achievement of the target. The model can handle multiple targets simultaneously. Market penetration of technologies is not pre-defined but is a result of the model depending on economics and behaviors. Technology learning is explicitly represented and depends on volume of anticipated sales.

Market penetration of alternative technologies and fuels in transport heavily depends on successful market coordination of various agents having different aspirations. At least four types of agents are identified: developers of refueling/recharging infrastructure aiming at economic viability of investment depending on future use of infrastructure; fuel suppliers who invest upstream in fuel production, the economics of which depend on market volume; providers of technologies used in vehicles and transport means who need to anticipate future market volume to invest in technology improvement and massive production lines in order to deliver products at lower costs and higher performance; consumers requiring assurance about refueling/recharging infrastructure with adequate coverage, and low cost fuels and vehicle technologies in order to make choices enabling market penetration of alternative fuel/technologies. The PRIMES model can be used to explicitly analyse the dynamics of market coordination with individual focus on stylized agents allowing for development of complex scenarios, which may assume different degrees of success in effective market coordination. Thus, projections of market penetration of alternative fuels/technologies are fully transparent and include the entire spectrum of interactions between consumer choices, technology learning, infrastructure economics and fuel supply.

The exogenous scenario assumptions are grouped as follows:

- Transport activity for passengers and freight
- Fuel prices, taxation of fuels
- Availability of alternative fuels and regulations on blending
- Other costs and taxations in transport
- Development of refueling and recharging infrastructure and coverage
- Cost parameters influencing public transport tariffs and infrastructure fees where applicable
- Regulations on technologies, standards on CO_2 or on energy efficiency performance of vehicles
- Measures and infrastructure influencing modal shifts and modal efficiency

- Taxations to internalise external costs (for example for air pollution, noise, accidents, etc.)
- Technical improvements and cost changes for various vehicle technologies
- Driving range for battery equipped and hydrogen fuel cell vehicle technologies
- Market coordination assumptions between infrastructure, technology learning and perception of fuel/technology maturity by consumers.

The policy measures which can be represented in the model can be grouped in soft, economic, regulatory and infrastructure measures, as listed in Table A.1-2.

Table A.1-2: Description of policy measures in PRIMES-TREMOVE

Policy measures	Description
Soft measures	Soft measures include the coordination between the public and the private sector, information campaigns, certification of services and labeling, partnerships between the public and the private sector aiming at enhancing knowledge and at using resources more efficiently. These kind of measures can be mirrored as factors improving the perceived cost of technologies by consumers, thus allowing for faster adoption of new or more efficient, but also more expensive, technologies. In the absence of such measures, the model assumes higher perceived costs in the form of risk premiums for new technologies, which discourage consumers. Policies that decrease uncertainty or risk (technical, financing, regulatory. etc.) surrounding consumer choices can be mirrored by reducing risk premium factors and by lowering discount rates which are involved in capital budgeting decisions simulated by the model. The perceived cost parameters also reflect anticipation by consumers and can vary in order to mirror the anticipation confidence by consumers on commercial maturity of new technologies.
Economic measures	Economic measures aim to influence consumer choices by modifying relative costs and prices of fuels and technologies. They include subsidies and taxes on fuels, vehicles, emissions, congestion and other externalities such as air pollution, accidents and noise. Certificate systems such as the ETS are also explicitly modelled. The level of the ETS carbon price is determined in the core PRIMES model. Measures supporting R&D are reflected on costs and performance characteristics of new technologies. Taxation or subsidization policies can be mirrored in scenarios at relatively high resolution: they can be defined for specific technologies (e.g. subsidies to BEVs), for new versus old vehicles, they can vary by size of vehicle, they can be linked to vehicle performance in terms of efficiency or emissions, they can take the form of tax exemptions (e.g. exemption from registration tax for new alternative vehicles), they may apply on fuels, they can vary by vehicle age etc. Economic measures are also modeled for public

Policy measures	Description
	transport (for example to influence ticket prices) and for non-road transport. Fuel taxation is modeled through the standard excise taxes which can be defined either in standard form, or in proportion to emissions (direct or life cycle) or energy efficiency.
Regulatory measures	Regulatory measures include the setting of targets and technology standards. EU regulations No 443/2009 and No 510/2011 setting emission performance standards for new passenger cars and new light commercial vehicles, respectively, as part of the European Union's integrated approach to reduce CO_2 emissions from light-duty vehicles have been explicitly integrated into the model. Tailpipe CO_2 emission standards measured in gCO_2/km, which apply on new vehicle registrations, are constraints influencing the consumers' choices upon purchasing new vehicle. In similar way, energy efficiency performance standards for all road transport modes have been integrated in the model. These standards set an efficiency constraint on new vehicle registrations. The current as well as future EURO standards on road transport vehicles are explicitly implemented and are important for projecting the future volume of air pollutants in the transport sector and determining the structure of the fleet. The model includes a special routine, which simulates how the regulations imposing standards influence supply (structure by technology and vehicle prices) by vehicle manufacturers in order to influence consumer choices therefore allowing compliance with standards. Technology standards are also handled in the model for non-road transport technologies. Targets on emissions or energy can be imposed by transport sector or overall. Targets influence consumer choices through shadow prices (associated to each target type) which are perceived by the consumers as costs or benefits. Such shadow prices, including carbon values, can be coordinated with the rest of PRIMES model.
Infrastructure measures	Development of refueling/recharging infrastructure for alternative fuels (electricity, hydrogen, LNG, CNG, etc.) is policy-driven. Geographic coverage is determined as part of the policy assumption and concern road and maritime transport. The model simulates perception of infrastructure availability by consumers and depending on the matching between geographic coverage and trip types availability influences consumer choices. Investment cost recovery options are included. The model does not explicitly represent transport infrastructure changes and improvements (e.g., intelligent systems, improved logistics) but it is possible in scenario design to mirror cost, efficiency and modal shift impacts of these policies.

A.1.2.4 Model Structure: Demand and Supply Equilibrium

PRIMES-TREMOVE solves a sort of market equilibrium between demand for transport services and supply of transport services.

The model fully captures the features of demand and supply matching, which prevail in transport sector: part of the supply of transport services is carried out by the same person who is a demander for such services; in other words, supply is split between self-supply of transport services and the purchasing of transport services from transportation companies.

There are fundamental differences between self-production of transport services and purchasing from transport businesses: to self-supply the service, the consumer (individual or firm) faces both capital and variable costs, where capital costs correspond to the purchasing of transportation means, whereas, when purchasing transport services from transport suppliers, the consumer faces only variable costs (corresponding to ticket prices). Transportation companies also face capital and variable costs but sell services at transport tariffs (ticket prices, etc.).

In addition, there is no capital rent in self-supply of transport services and the consumer chooses between alternative self-supply solutions by comparing total costs, assuming average cost pricing of alternative solutions. This contrasts with prices set by transportation companies, which are often based on marginal costs and may allow for capital rents (e.g. aviation). Other transportation companies, owned by the state and subject to strong price regulation, apply average (instead of marginal) cost pricing rules to determine transportation tariffs.

To find the equilibrium between demand and supply of transport services, PRIMES-TREMOVE considers transport prices as a pivot influencing both demand and supply.

To include external costs and also other costs, such as congestion, the model includes additional components in the equilibrium enabling prices, which is termed “generalized price of transportation” and is calculated both for self-production and for business supply of transport services.

Based on the above mentioned approach, PRIMES-TREMOVE solves an equilibrium problem with equilibrium constraints (EPEC) simultaneously for multiple transport services and for multiple agents, some of which are individual consumers. Others are firms, which demand or produce transport services. The EPEC formulation also includes overall constraints which represent policy targets (e.g., on emissions, on energy, etc.) which influence both demand and supply. Mathematically, the model is solved as a non-linear mixed complementarity problem.

The transport demand module simulates mobility decisions driven by macroeconomic drivers which distribute transport activity over different transport modes and trip types, so as to calculate transport services by mode for both individuals and firms. The decision process is simulated as a utility maximization problem under budget and other constraints for individual private passengers and as a cost minimization problem for firms.

The transport supply module determines the mix of vehicle technologies (generally the transportation means), the operation of transport means by trip type and the fuel mix so as to meet modal transport demand at least cost. In case of supply by transportation companies, the module calculates transportation tariffs (ticket prices). Consumer or firm choices at various levels of the supply module use total costs, inclusive of capital costs, or only variable costs, as appropriate. For example purchasing a new car involves total cost comparisons among alternative solutions, but choice of fuel type for an existing car, if that is possible, or determining the rate of use of an existing car naturally involves only variable costs. The choice of technology is generally the result of a discrete choice problem which considers relative costs which optionally include factors indicating impacts on externalities.

Solving for equilibrium also includes computation of energy consumption, emissions of pollutants and externality impacts related to the use of transportation means. Optionally, policy targets related to externalities (or overall efficiency or overall emissions) may become binding in equilibrium. Through the mixed complementarity formulation of the model, such overall constraints influence all choices in the demand and supply transport modules.

Both the demand and supply modules are dynamic over time, simulate capital turnover with possibility of premature replacement of equipment and keep track of equipment technology vintages. Foresight assumptions are optional, and by default, foresight is limited to two 5-year time periods.

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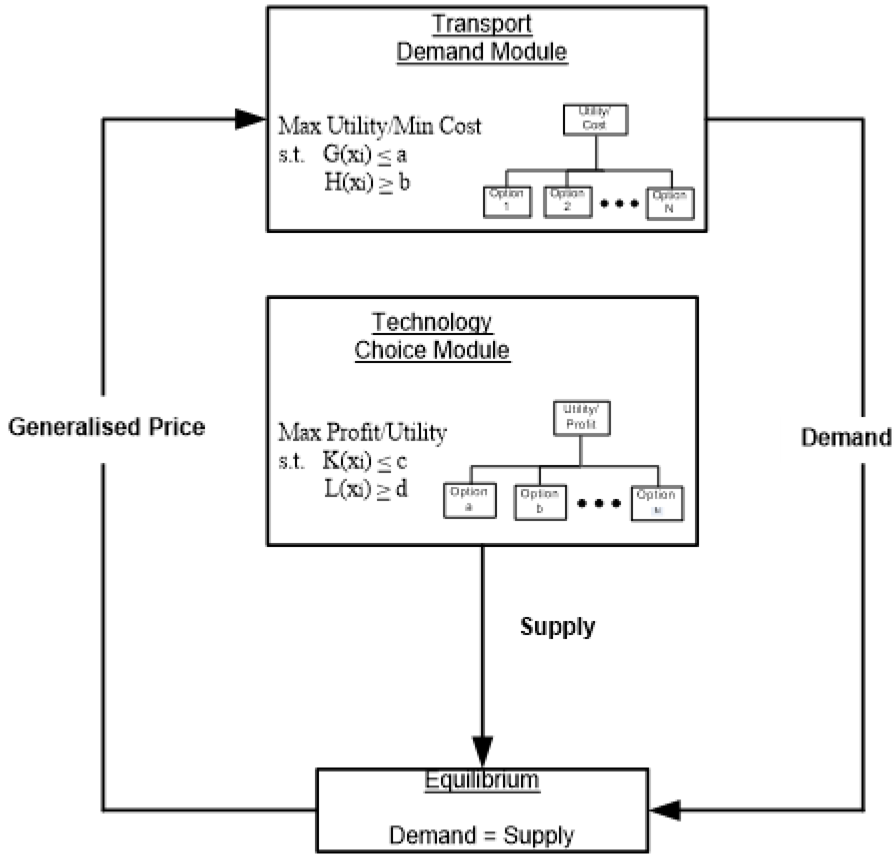
Figure A.1-4: Demand and supply equilibrium scheme



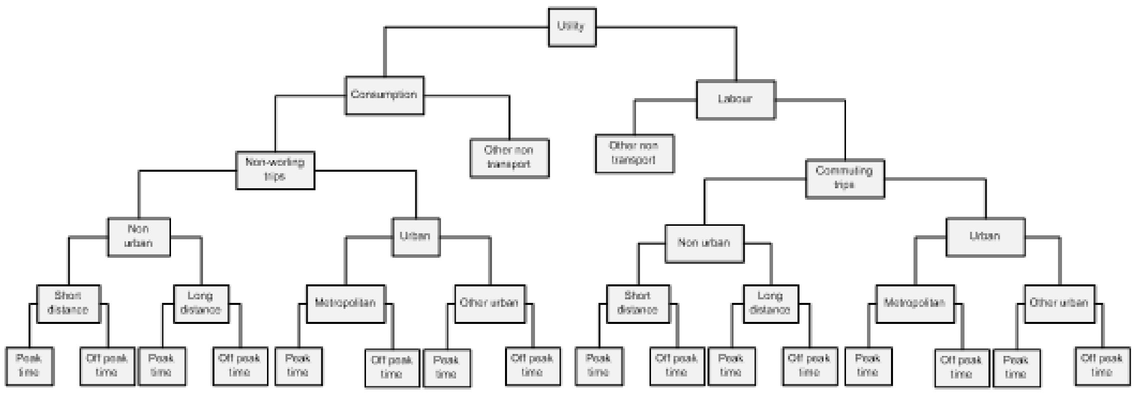
A.1.2.5 The Transport Demand Module

The transport demand module simulates the decision process of representative agents in defining total mobility and allocating mobility to a predefined set of transport modes and of trip types by mode. The model distinctly treats private passenger transportation and transportation driven by economic activity, such as movement of products and business trips. The former involves individuals deriving utility from mobility, whereas the latter involves firms needing mobility for business purposes.

Representative individuals, i.e. passengers, are formulated to maximize a utility function subject to income constraint. Utility is derived from transport activity and also from consumption of goods and services not related to transportation. Thus, substitutions are possible between transportation and non-transportation expenditures, when for example relative costs of transportation increase.

Allocation of income to expenditures in transportation services and non-transportation goods and services is derived from optimization. The projection of income is exogenous and is based on macroeconomic growth scenarios. Allocation of income to different utility inputs is organized as a tree involving choices at consecutive levels.

Figure A.1-5: First sub-tree



Utility formation is formulated using a nested Constant Elasticity of Substitution (CES) function. Concerning transportation-related choices, a first part of the tree involves trip types which are organized as a sub-tree which consecutively deals with trips by purpose, trips by geographic area and trips by distance classes.

The second part of the overall tree for passenger transport involves distribution across transport modes of mobility by trip type. The corresponding sub-tree, allocates mobility between aggregate transport modes, such as public and private, and further down it allocates activity to more disaggregated transport modes such as private cars (disaggregated by size), two wheelers, buses for urban trips, coaches for inter-urban trips, aviation, rail, inland navigation, metro and trams where applicable.

Figure A.1-6: Second sub-tree (example 1)

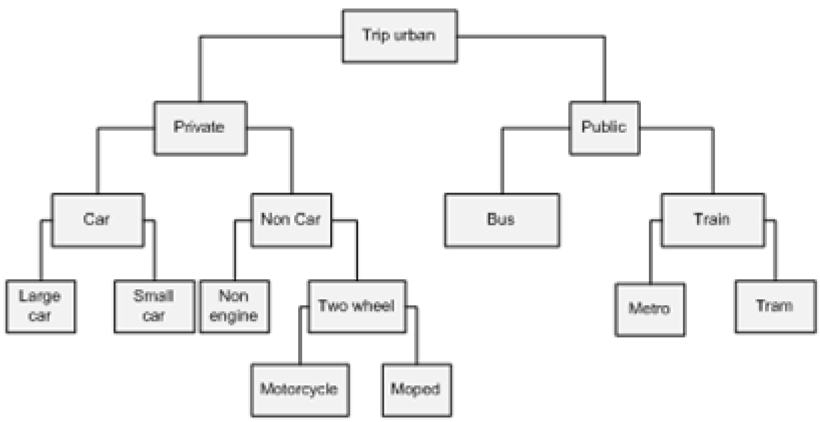


Figure A.1-7: Second sub-tree (example 2)

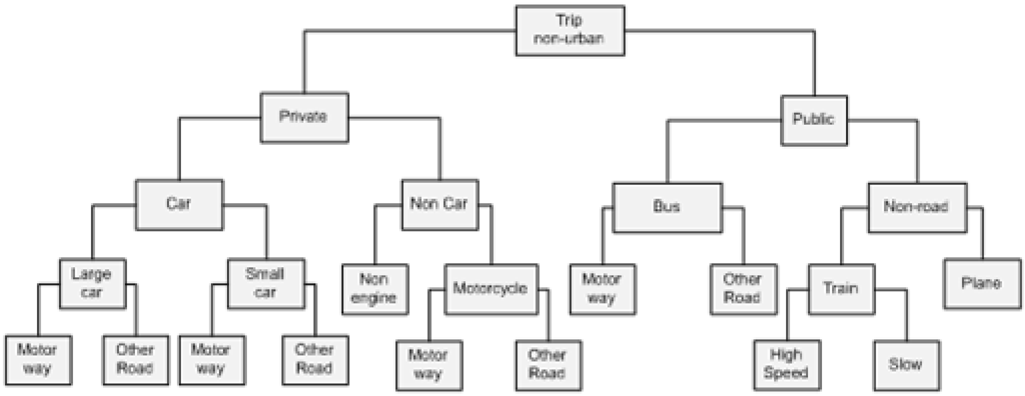


Figure A.1-8: Business transport activity tree (example 1)

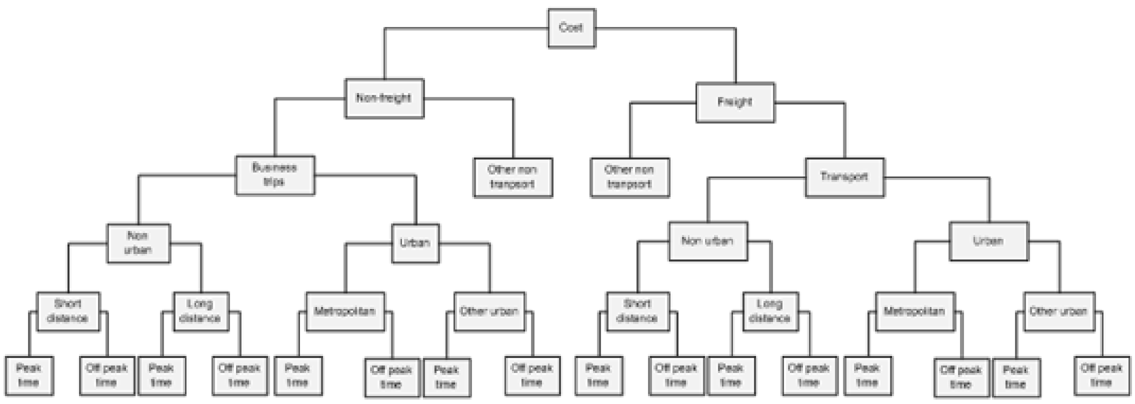


Figure A.1-9: Business transport activity tree (example 2)

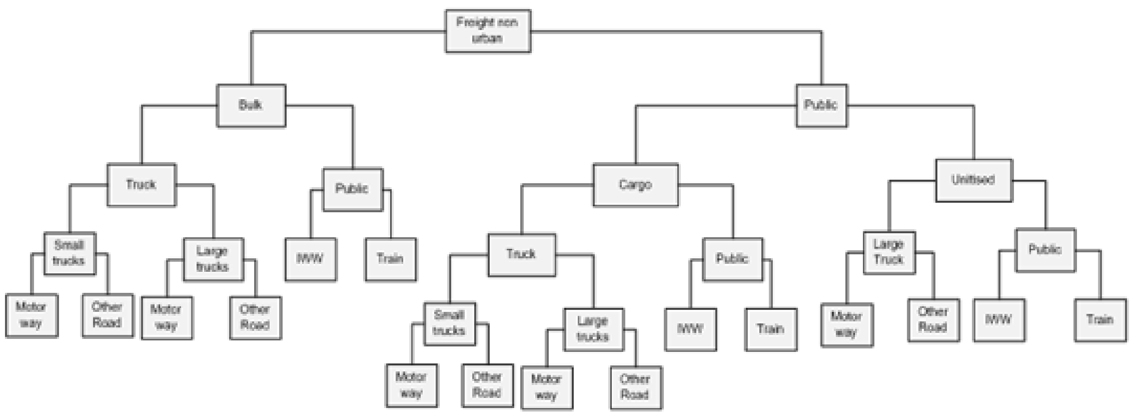
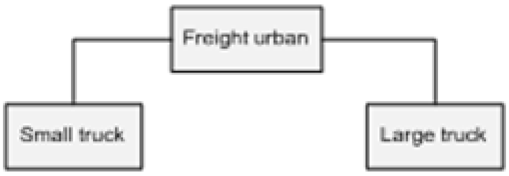


Figure A.1-10: Business transport activity tree (example 3)



Both for passenger and freight transport, mobility allocation differentiates trips between trip at peak or at off-peak times. The level structure of the trees allows to specify different values of elasticity of substitution by level so as to better capture the degree of substitutability between mobility choices. A low elasticity corresponds to choices that are close to be complementary to each other (in other words allocation is based on almost fixed proportions), whereas a high elasticity value signifies that choices are substitutable to each other.

The constant elasticity of substitution functional forms are calibrated to past year statistics. The official statistics of transport activity (e.g. EUROSTAT and DG MOVE Pocketbook) include aggregate decomposition of activity. Disaggregation up to the tree structure of the model has been based on transport surveys, on TREMOVE model data and on accounting techniques (Excel-based models). Validation of the calibrated transport demand model has been performed by running the model over a large set of different assumptions about exogenous parameters, calculating aggregate elasticities and comparing them to econometrically estimated elasticity values as reported in the literature.

Generally the values of elasticity substitutions in the CES transport activity functions are small, which implies that modal shifts are rather inflexible, as confirmed by several empirical studies found in the literature. Aiming at simulating long-term structural changes, including the mix of transport modes, the model uses a “shifting” technique which applies on the scale parameters of the CES functions and allows to represent the effects of policies and infrastructure investments, driving modal shifts at higher degrees than observed in the past. Intelligent transport systems, new transport infrastructure, congestion management policies acting in favour of public transport in the cities, inter-modal facilitation techniques, improved logistics, etc. are examples of interventions that can accelerate modal shifts, in particular in favour of public transport and rail. PRIMES-TREMOVE does not represent these interventions in an explicit manner, because it lacks appropriate spatial resolution, but it can mirror their effects on modal shifts in scenarios, provided that detailed transport studies have measured these effects.

The optimization models for passenger and for business transport activity use unit prices/costs which are associated to each node of the bottom level of the trees and refer to specific transport modes for specific trip types. These prices/costs are calculated in the model of transport services supply. The unit costs of upper tree levels are calculated from minimum cost functions derived from the optimization.

A.1.2.6 The Transport Services Supply Module

The transport services supply module determines the mix of transport means technologies, the mix of fuels and the rate of use of transport means so as to meet demand for transport services as given by the transport demand module. For this purpose, a cost minimization model is solved which incorporates discrete choice behavioral models at various levels. Based on the results of cost minimization, unit prices/costs are calculated following explicit pricing and appropriate cost accounting rules for each transport mode. These unit prices/costs may optionally include external costs. Demand for transport services depend on these unit prices/costs, and so a loop is established between demand and supply of transport services.

A specific transport means can serve for more than one trip, which have different characteristics in terms of geographic area, peak or off-peak time and distance. This is taken into account in establishing how supply matches demand for transport services. The unit price/cost by mode depends on the characteristics of the trips served by this mode.

Stock-flow relationships are fully captured in tracking evolution of transport means fleet (vehicles, trains, vessels, aircrafts). The model considers stock of transport means inherited from previous time periods, calculates scrapping due to technical lifetime, evaluates the economics of possible premature scrapping and determines the best choice of new transport means which are needed to meet demand. The model also calculates the degree of using the transport means by trip type and so it calculates the unit costs of trips. To do this, the fuel mix is also chosen endogenously. The calculation involves all steps and options simultaneously. Balancing of demand and supply is obtained for each time period. The choices are based on cost minimization which includes anticipation factors.

The choices involve adoption of specific technologies and fuel types; technical and economic characteristics of adopted technologies are inherited in future times when using the adopted technology. The model follows a vintage capital approach for all transport means which means that dynamically it keeps track of technology characteristics of transport means according to vintages. Not only latest technologies are available in the choice menu in a given time period; the model allows for choice of older technologies, if that is permitted by legislation. which may have lower costs; thus the model captures behavioral inertia and also market features, such as the possibility of purchasing second hand vehicles.

1. Choice of new transport means. Costing methodology

There are several factors influencing the choice of a new transport means. They include payable and non-payable elements. The former include true payments (internal costs) and external costs (when internalised); the latter include indirect costs as perceived by decision makers.

True payable costs include all cost elements over the lifetime of the candidate transport means: purchasing cost which is interpreted as a capital cost; annual fixed costs for maintenance, insurance and ownership/circulation taxation; variable costs for fuel consumption depending on trip type and operation conditions; other variable costs including congestion fees, parking fees and tolled roads.

To compare candidate transport means, a total cost index is calculated which aggregates all cost elements on an annual basis. Only capital costs are upfront costs and so they are transformed in annuity payments. The transformation uses a discount rate which is conceived as opportunity cost of drawing funds by the decision maker. It is calculated as a weighted average cost of capital, which adds equity capital valued at a subjective discount rate (which is higher for individuals and lower for businesses) and borrowed capital valued at lending interest rate.

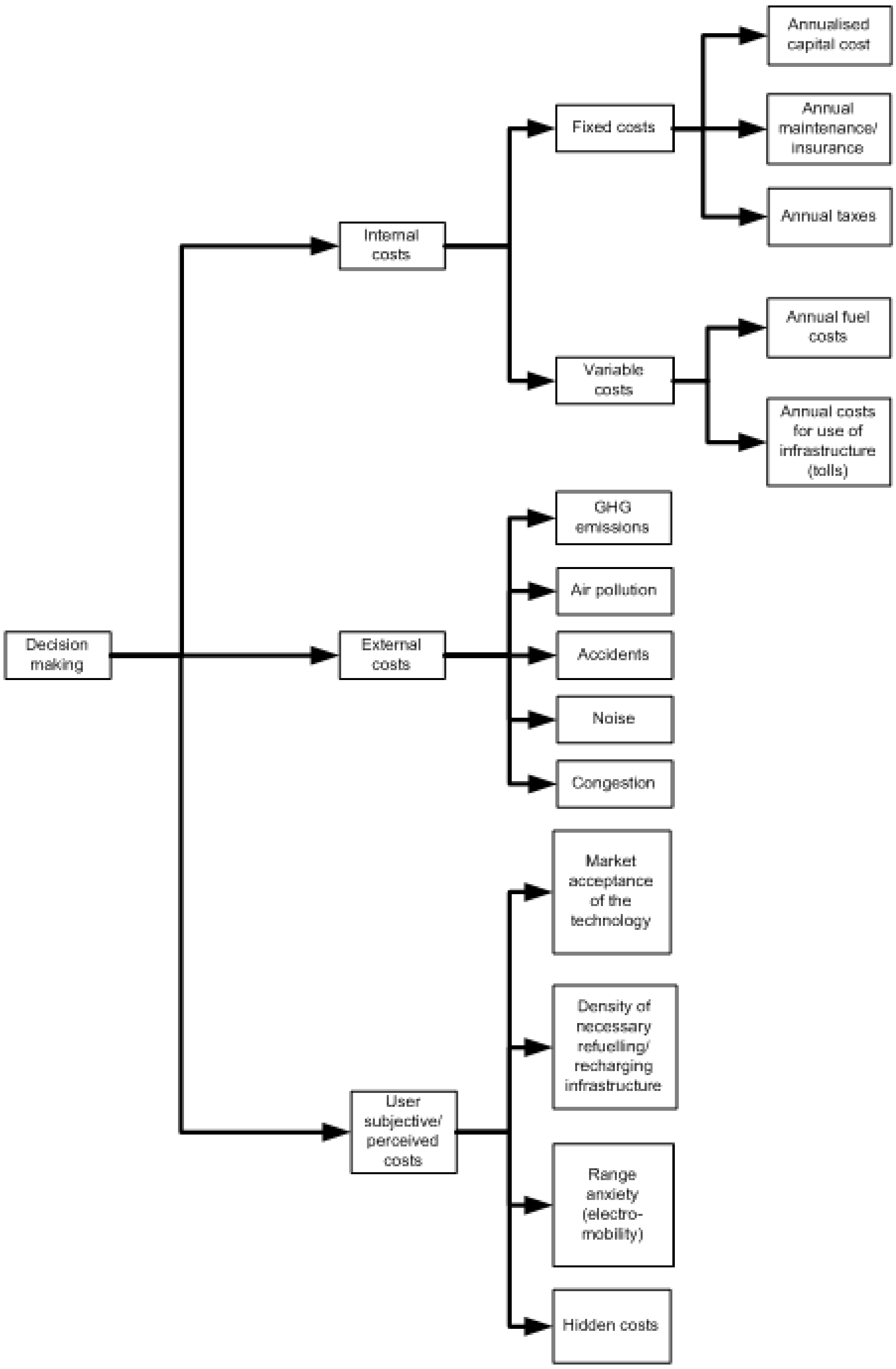
Risk premium is also added which has several components differentiating sectors (private versus public), type of decision maker (higher risk for individuals) and type of technology (higher risk for yet immature technologies). The capital cost parameters can be changed by scenario and over time so as to mirror policies and evolutions which affect risk premium factors.

The purchasing costs of new technologies are assumed to evolve dynamically, according to learning curves which depend on cumulative sales and technology support policy (varying by scenario), reflecting economies of scale from mass production. Similar learning curves are included for car components such as batteries or fuel cells.

Multiple external cost categories are due to transportation. They refer to congestion, accidents, noise and air pollution and they are evaluated in physical and monetary terms by the model. Monetary values are based on the Updated Handbook of Internalisation of External Costs, published by the European Commission.

Other factors which do not necessarily imply true payments by the user but may imply indirect costs are influencing decisions about choice of new vehicles (and generally transport means). The model includes perceived cost factors reflecting: technical risk of yet immature technologies, acceptance factors representing market penetration (this factor serves to simulate accelerated market diffusion), density of refueling/recharging infrastructure applicable to technologies using alternative fuels and those that have range limitations.

Figure A.1-11: Schematic representation of factors influencing choice of new transport means



2. Commercial maturity influences technology choice

Market acceptance factors are used to simulate circumstances where consumers have risk avert behaviors regarding new technologies when they are still in early stages of market deployment. Perception of risk usually concerns technical performance, maintenance costs and operation convenience. When market penetration exceeds a certain threshold, consumers imitating each other change behavior and increasingly accept the innovative technologies giving rise to rapid market diffusion. Both stages of market deployment are captured in the model through appropriate values of market acceptance factors which are part of scenario design. So the model can simulate reluctance to adopt new technologies in early stages of diffusion and rapid market penetration, often leading to market dominance, in later stages.

3. Infrastructure influences technology choice

The decision making is also influenced by the availability of infrastructure and the range provided by each vehicle technology; these features are particularly important when new fuels or new technologies enter the market. In order to represent in a more refined manner the true effects of the range limitations of some vehicle technologies and the lack of adequate infrastructure of alternative fuels, the trip categories represented into the model are assumed to follow a frequency distribution of trip distances. The model assumes that decision makers compare the range possibilities of each vehicle technology and the availability of refueling/recharging infrastructure for all classes of trip types and trip distances and apply cost penalties in case of mismatches between range limitations or non-availability of refueling and trip types or trip distances. Thus, a vehicle or fuel type may not becoming competitive due to mismatches compared to other options which do not present such limitations. The mismatching considerations do not apply to conventional technologies such as the ICEs and are relevant for BEVs and FCEVs, as well as for alternative fuels such as electricity, hydrogen, methane, LNG, biofuels, etc. The refueling/recharging infrastructure applies to road and to maritime transport networks and ports, respectively.

4. Specific fuel consumption

Specific fuel consumption of each vehicle type is endogenously determined by the model and is calculated based on the COPERT methodology. The COPERT methodology enables calculation of fuel consumption of road vehicles as a function of their speed, which is determined by the endogenously calculated travelling time and the average mileage of trips per type of road transport mode. The complete COPERT methodology has been integrated into the model providing a strong analytical tool for the calculation of the consumption of various fuels and consequent calculations of costs. For other technologies not included in COPERT such as BEVs and FCEVs, data from literature and other studies are used. Similar approaches have been followed in the model to calculate specific fuel consumption by vehicle type and by trip type for bus/coaches and for heavy duty vehicles.

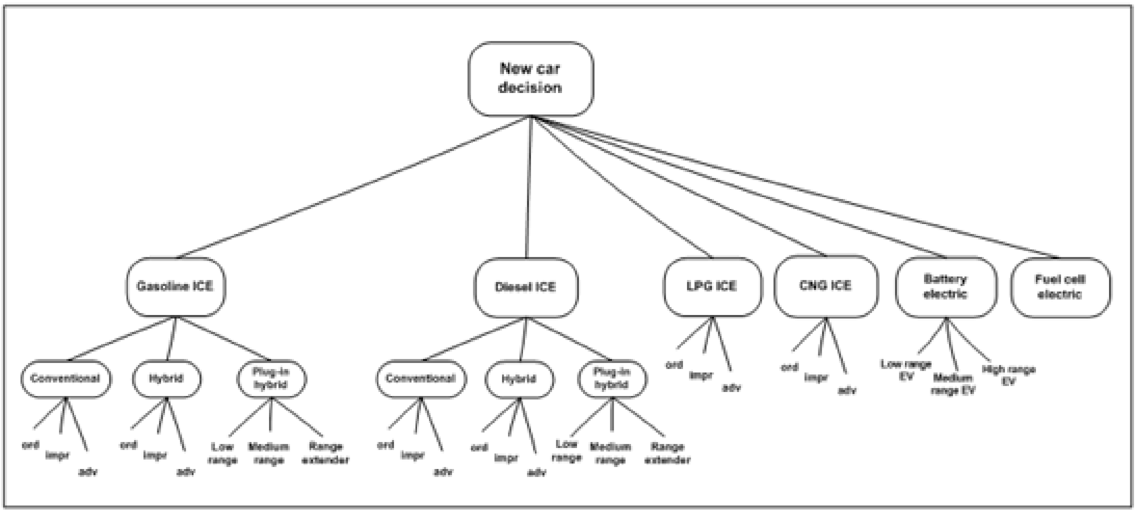
The COPERT methodology enables calculation of fuel consumption of road vehicles as a function of their speed, which is determined by the endogenously calculated travelling time, the average mileage of trips per type of road transport mode, the occupancy factor for passenger trips and the load factor for freight transportations. The complete COPERT methodology as fully integrated into the model also serves to calculate emissions of pollutants, including NOx, CO, SO2, PM and VOC.

The calculation of fuel consumption for hybrid vehicles has been modelled in such a way that it takes into account the region in which the vehicle is moving. For urban regions, the fuel savings are significantly higher than in non-urban ones because of traffic congestion and the slower average speeds that lead to more braking and thus to more energy being regenerated by the hybrid powertrain.

As far as plug-in hybrid cars are concerned, they are assumed to operate both as pure electric vehicles and as hybrids. The electric operation depends on the battery capacity which indicates an average pure electric mileage between charges. When the battery supplies are exhausted, the vehicle switches to a hybrid mode burning conventional fuel. Plug-in hybrid types with range extending engines are also included. The model includes pure electric vehicles as following a single all electric operation equipped with high capacity batteries. Electricity consumption for plug-in hybrids and pure electric vehicles is being calculated using efficiency figures drawn from literature.

The choice of technology and fuel type when purchasing a new vehicle is represented in the model as a discrete choice model following a nested Weibull formulation. The upper level of the decision tree includes ICE types, battery-based electric cars and fuel cell cars. The next level distinguishes between conventional, hybrid and plug-in hybrids. Each of these car types is further disaggregated in technology types, regarding efficiency for conventional cars, range for electric cars, etc.

Figure A.1-12: Car decision tree



5. Fuel Choice

The model includes possibility of fuel choice for some vehicle technologies. The choice depends on relative fuel costs of vehicles. Cost penalties apply for fuels with poorly available refueling infrastructure. A logistic function is used to calculate the frequencies of alternative fuel choices. For example a diesel vehicle can refuel with diesel blend or pure biodiesel if technically feasible.

6. Scrapping of Vehicles

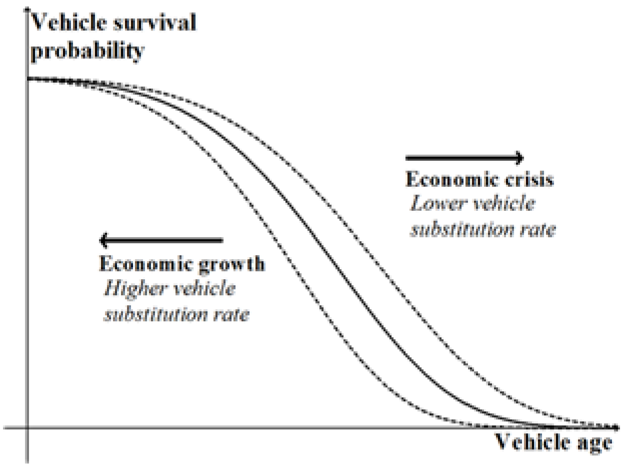
The capital vintage model includes normal scrapping and possibility of premature scrapping for economic reasons.

Normal scrapping is represented using a distribution function (two parameters Weibull reliability function) with calibrated parameters by country. The distribution function indicates the survival probability of a vehicle type as a function of time after date of purchase. The model includes dependence of parameter values on income expectation, so as to capture scrapping rates reducing in periods of low economic growth and increasing in periods of sustained growth. For low income countries scrapping rates are high but they may reduce rapidly with economic growth.

Low usage rates of yet not scrapped old vehicles are endogenous in the model through the determination of annual mileage by type of vehicle and by vintage. The driver in the model is economic cost of using a vehicle; obviously costs (fuel and environmental) increase with age and mileage decreases.

Premature scrapping of a vehicle is endogenous and occurs when fixed and variable operating costs are higher than total costs (including annuity payment for capital) of a new vehicle. To capture other drivers, related to behavioral features, the model uses a logistic function to calculate the frequency of premature scrapping.

Figure A.1-13: Scrapping of vehicles influencing choice of vehicles



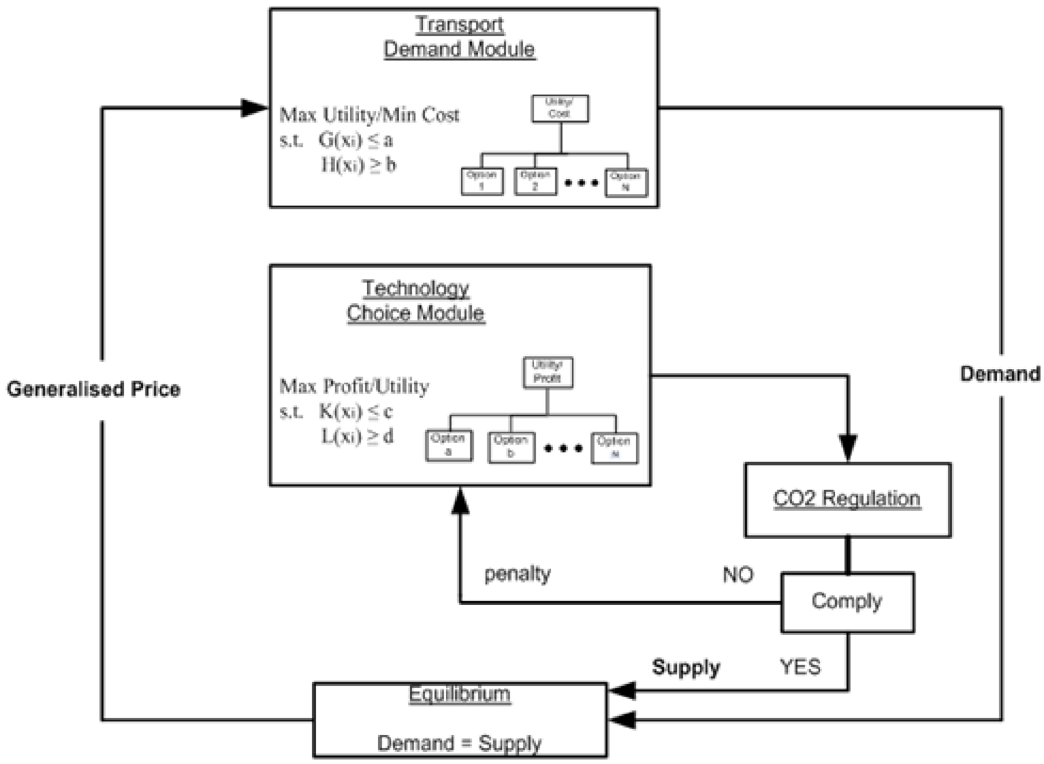
The model includes several present and future regulations which influence choice of vehicle technologies. The EURO standards on pollutant emission performance are explicitly represented in the model for all types of vehicles. The model relates EURO standards with vehicle vintages and it specifies that only vehicle types which are compliant with the applicable EURO standard are available for choice in each period of time.

7. Standards on Specific CO_2 Emissions

The standards on specific CO_2 emissions (e.g. EU regulations No 443/2009 and No 510/2011) are modelled as constraints applying on average emission performance over all new vehicles that are available for choice. It is assumed that average specific CO_2 emissions of the fleet sold by manufacturers in a period of time must not exceed the specific emission standard as applicable, otherwise a high penalty applies. The specific CO_2 emissions of each vehicle are measured through the New European Driving Cycle (NEDC). A CO_2 label is thus associated to each vehicle type.

Average label for new registrations is computed by weighting labels by vehicle type using the shares of each vehicle type in new registrations. These shares are endogenous in the model and depend, among others, on the costs of purchasing new vehicles. If the average label is higher than the applicable standard, the model applies a cost penalty on the purchasing costs of each vehicle type proportionally depending on the difference between the vehicle's label and the standard. As the purchasing costs of vehicles are modified, consumers are simulated to change the decisions and so the mix of new registrations is modified towards a lower average label. This process continues until average label is exactly equal to the standard.

Figure A.1-14: Modeling of CO_2 emissions standard



The model also represents other labeling policies and standards as policy options. Energy efficiency labels and standards are such an example. They can be measured either in final energy or in primary energy terms. Mixed labeling and standards are also possible.

Obviously, the choice of standards influence future mix of vehicles and this is fully captured in the model. For example, very strict end-of-pipe CO_2 standards would equally incite battery-based and fuel cell cars, but strict final energy efficiency standards would promote battery-based rather than fuel cell cars.

Moderate CO_2 or efficiency standards can be met also by conventional car technologies provided that they become more efficient. Cost-efficiency curves are modeled for all conventional technologies (and for various technologies and vehicle types in road transport) to represent a locus of efficiency improvement possibilities. The cost-efficiency curves have a time dimension and also have increasing slopes, which signify that purchasing costs increase with efficiency but the incremental costs decrease over time.

8. Cost of Time influences Transport Costs

Cost of time represents a monetary valuation of travelling time which differs between individual and business passengers, and also differs among transport modes depending upon temporal and geographical features. Cost of time is subdivided into cost of time for non-road and road transport. Cost of time is expressed as the product of traveling time and the value of time, used to represent the value of travel time which differs between the trip types. Travel time is directly influenced by traffic congestion and, in the case of road transport, a congestion function is used in calculations. For public transport, cost of time also includes waiting time which is also influenced by congestion.

The traveling time is calculated with distinction between metropolitan, other urban, motorway and other road areas, and depends on allocation of mobility to different trip types, as calculated in the transport demand module. Traveling time also depends on exogenously defined parameters denoting infrastructure investment and expenditures for the creation of parking places. Traveling time for non-road transport is exogenously defined, taking into account average mileage and speed.

Cost of time is included in the calculation of generalized price of transportation.

9. Rail Transport

Demand for rail transport (passengers and freight) as well as substitutions between rail and road transportation are covered in the transport demand module. The transport supply module aims at finding the mix of train types and fuel types to meet demand. For this purpose, a discrete choice methodology determines the structure of the train fleet, by distinguishing between metro, tram, urban and non-urban trains as well as high speed rail. A capital vintage approach is implemented also for rail. Choice of new types of rail transport is simulated through a logistic share function that depends mainly on total operational costs and takes into account capital costs, fuel consumption, emissions etc. The stock of existing rail infrastructure is taken into account through an aggregate indicator which influences the degree of renewal of the train fleet. The model endogenously calculates mileage per vehicle technology, rail type and train vintage by taking into account relative variable costs and the influence of regulations. The model includes engineering-based formulas to calculate specific fuel consumption by train type and vintage and thus it derives total fuel consumption and emissions. Cost-efficiency curves, conceived as reduced-form representations of various efficiency improving techniques, are included for train technologies.

10. Air Transport

Demand for air transport distinguishes between trip distance classes and also between domestic, intra-EU and international flights.

Table A.1-3: Airplane distance classes

No.	Airplane distance classes
1	< 500
2	500 - 1000
3	1000 - 1500
4	1500 - 2000
5	> 2000

The air transport supply module determines investment in new aircrafts, finds a mix of stylized aircraft technologies, and calculates fuel consumption and emissions. The model includes a few stylized aircraft technologies, namely ordinary, improved and advanced which in that order have higher investment costs and higher energy efficiency. The efficiency possibilities are drawn from aggregate cost-efficiency curves, which are parameterized based on literature data. Specific fuel consumption is based on engineering-type formulas, drawn from literature, and the calculation distinguishes between distance classes of flights. The only alternative fuel possibility is to use blends with bio-kerosene. The blending rates are exogenously defined and are depending on emission reduction objectives (signalled through carbon prices) and assumptions about biofuel supply possibilities (which are included in the biomass supply and bio-fuel blending models). Inclusion of aviation in the EU ETS is explicitly modeled.

11. Maritime Transport

Maritime transport refers to inland navigation and distinguishes between short sea shipping and inland water ways, as well as between freight and passenger transport. Vessel types refer to stylized technologies (ordinary, improved, advanced). Cost-efficiency curves capture possible energy efficiency improvement in relation to capital costs. Choice of fuels includes conventional mineral oil, blended bio-fuels and LNG.

A separate model projects activity and energy consumption for international maritime bunkers. Activity is projected using a simplified world trade model covering EU imports-exports with distinction of ships carrying hydrocarbons, bulk cargo and containers. Separate drivers are considered for each category and for energy bulk cargo the model links to energy imports-exports of the EU. Allocation to EU ports is based on exogenous parameters and time trends. Energy consumption is based on specific fuel consumption functions which use cost-efficiency curves to summarize efficiency possibilities. Alternative fuels include bio-fuels and LNG.

A.1.2.7 Generalized Price of Transportation

As mentioned before, the transport supply module projects the structure of the vehicle, train, aircraft and vessel fleet together with fuel consumption and emissions. The calculations are based on simulated decisions which can be grouped as follows:

- Normal scrapping
- Premature scrapping of old stock of vehicles
- Requirements for new vehicle registrations
- Allocation of new vehicle registrations into different technologies
- Fuel choice
- Annual mileage per vehicle type and vintage which is further distributed by trip type.

At this stage, fuel consumption and emissions are calculated. Policy driven regulations and standards influence the simulated choices.

The above mentioned decisions imply expenditure for purchasing transport means, for fixed and variable operating costs and for externalities, if and where applicable. The model calculates an indicator of unit cost of transportation by mode and trip type, inclusive of all cost elements, the cost of time and external costs if applicable.

The unit cost is based on average costs for self-supply of transportation services and on tariff setting rules for business-supplied transportation services. The rules mirror current practices and regulations concerning ticket and tariff setting by transportation businesses and generally combine marginal cost and average cost pricing. For aviation, marginal cost pricing is assumed to prevail. For rail and road public transport, average cost pricing is assumed with partial recovery of fixed capital costs, depending on assumptions about subsidies. Fixed cost recovery is distributed across customer types using a Ramsey-Boiteux methodology.

The calculated unit cost of transportation by mode and trip type is termed “generalized prices of transportation” and is conveyed to the transport demand module where it influences demand for transportation services. The interaction through the generalized prices of transportation ensures equilibrium between demand and supply of transport services.

The transport demand and the technology choice modules reach equilibrium through the generalized price of transportation. The generalized price is determined once the structure of the vehicle fleet is defined (at minimum cost) by the technology choice module to meet the projected demand derived from the transport demand module. The generalized price of transportation differs among the transport modes and across the various trips and regions. It is also endogenously defined as a result from an interaction between the demand and the technology choice modules.

A.1.2.8 Refueling/Recharging Infrastructure

As mentioned above, the availability of refueling or recharging infrastructure has an impact on vehicle and fuel choices. Aiming also at supporting cost-benefit analysis, PRIMES-TREMOVE includes a block of modules on refueling/recharging infrastructure development.

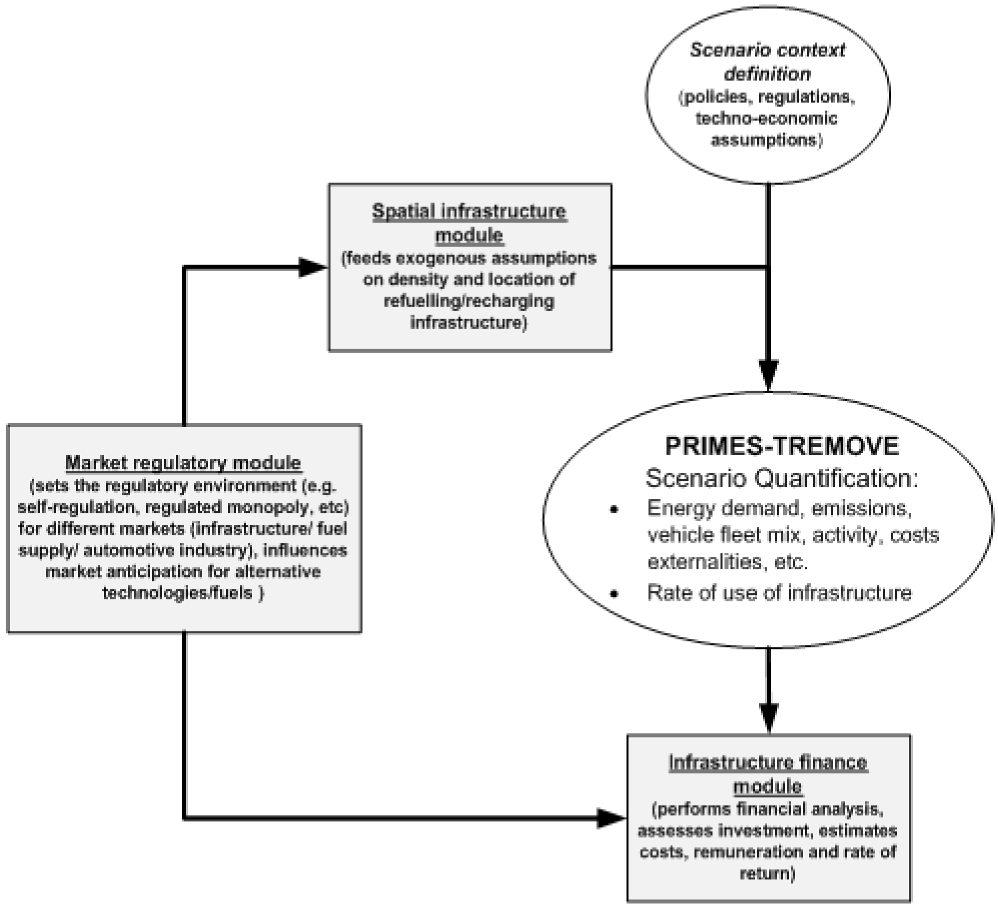
The refueling/recharging infrastructure is represented for urban, semi-urban and inter-urban categories per country, as a density of refueling/recharging points. The projection of densities is exogenous and part of scenario design.

The density of infrastructure of different fuels in various areas is connected to agents' traveling habits (represented through stylised histograms of trip distances). The combination is modeled as a driver of vehicle/fuel choice.

The fuel types with explicit infrastructure modeling are grid electricity, hydrogen, CNG gas, LNG gas, LPG, biogas and liquid bio-fuels (when there are separate dispensers for bio-fuels). Specific infrastructure assumptions are included for larger and heavier vehicles like HDVs and buses and for vessels (e.g. LNG in ports).

The infrastructure finance module calculates investment and O&M costs of the infrastructure by category, as well as revenues which depend on the scenario specification about infrastructure tariff method, funding and remuneration. Using model-derived rates of use of the infrastructure, the module calculates infrastructure remuneration and capital cost recovery, in case exogenously assumed tariffs are applied only to users of infrastructure. Alternatively, if tariffs are socialized (i.e. applied on all consumers), the module calculates the level of the tariff as required to recover capital costs.

Figure A.1-15: Modules on refueling/recharging infrastructure development



A.1.2.9 Calculation of External Costs

The main external costs in transport are congestion, accidents, noise and air pollution. Physical and monetary valuations are projected by the PRIMES-TREMOVE model.

The external costs of congestion denote the additional social cost incurred to the other users of the road infrastructure by an additional car. The model captures congestion impacts as changes from base year values due to vehicle activity depending on exogenously assumed changes in infrastructure. The calculation has limitations due to limited spatial coverage (stylized geographical areas) of the model. The aim of the model is to include a monetary valuation of congestion in the cost of time indicator which influences choices in demand and in supply of transport services.

Similarly, the model includes a simple calculation of impacts on accidents which is based on total activity of vehicles and on exogenous time trends. The impacts on noise are based on exogenous parameters which are differentiated by type of vehicle and technology.

The model calculates air pollution emissions as a function of fuel consumption, depending on vehicle and technology types and also depending on standards. Diffusion of pollution is not included.

Monetary valuation of externalities is based on average values drawn from literature and from the Update of the Handbook on External Costs of Transport (RICARDO-AEA et al. 2014). The model includes possibility to internalize externality impacts in various forms, such as inclusion of specific constraints (e.g. upper limits on physical evaluation of impacts) or as taxation on fuels or on vehicle types defined so as to reflect impacts on externalities. Obviously, the internalization influences vehicle and fuel choices and affects cost of transportation.

A.1.2.10 Measuring Disutility Costs

The PRIMES-TREMOVE model has a microeconomic foundation and solves a utility maximization problem for the individuals. When unit price of transportation increases for any reason, consumer’s utility (as well as the transportation activity) may decrease if substitutions are imperfect. Fuel price rises, taxation increase, emission constraints etc. are among the causes which drive reduction in transport activity.

In monetary terms, the utility level changes are measures following the income compensating variation method. This calculates the additional amount of income that consumers would require to allow increase in transport activity so as to compensate for the loss of utility due to the rise of unit price of transportation.

The disutility costs thus reflect the losses in utility (due to lower transport activity) of consumers in the context of a counterfactual scenario compared to a baseline scenario.

A.1.2.11 Classification of Transport Means

Table A.1-4: Classification of transport means

Category	Type	Technology
Small cars (<1.4l)	Gasoline	Pre ECE, ECE, Conventional, Euro I-V
	Bio-ethanol	Bio-ethanol blend, E85 FFV
	Hybrid Gasoline	Euro IV-VI
	Plug-in hybrid Gasoline	Plug-in hybrid technology
	Diesel	Euro IV-VI
	Bio-diesel	Blended Bio-diesel
	Synthetic fuels	Synthetic fuels

Category	Type	Technology
	Hybrid Diesel	Euro IV-VI
	Plug-in hybrid Diesel	Plug-in hybrid technology
	Battery electric	Battery electric technology
	Hydrogen	Hydrogen fuel cell
Medium Cars (1.4 - 2.0 l)	Gasoline	Pre ECE, ECE, Conventional, Euro I-V
	Bio-ethanol	Blended Bio-ethanol, E85 ethanol car
	Hybrid Gasoline	Euro III-V
	Plug-in hybrid Gasoline	Plug-in hybrid technology
	Diesel	Pre ECE, ECE, Conventional, Euro I-V
	Bio-diesel	Blended Bio-diesel
	Synthetic fuels	Synthetic fuels
	Hybrid Diesel	Euro III-V
	Plug-in hybrid Diesel	Plug-in hybrid technology
	Battery electric	Battery electric technology
	LPG	Conventional, Euro I-V
	CNG	Euro II-V
	Hydrogen	Hydrogen fuel cell
Large Cars (>2.0 l)	Gasoline	Pre ECE, ECE, Conventional, Euro I-V
	Bio-ethanol	Blended Bio-ethanol, E85 ethanol car
	Hybrid Gasoline	Euro III-V
	Plug-in hybrid Gasoline	Plug-in hybrid technology
	Diesel	Pre ECE, ECE, Conventional, Euro I-V
	Bio-diesel	Blended Bio-diesel
	Synthetic fuels	Synthetic fuels
	Hybrid Diesel	Euro III-V
	Plug-in hybrid Diesel	Plug-in hybrid technology
	Battery electric	Battery electric technology
	LPG	Conventional, Euro I-V
	CNG	Euro II-V
	Hydrogen	Hydrogen fuel cell

<table>
<tr><th>Category</th><th>Type</th><th colspan="3">Technology</th></tr>
<tr><td rowspan="4">Motorcycles</td><td>2-stroke technology, Gasoline, biofuels</td><td colspan="3">Conventional</td></tr>
<tr><td>Capacity 50-250 cc</td><td colspan="3">4-stroke technology using gasoline/biofuels</td></tr>
<tr><td>Capacity 250-750 cc</td><td colspan="3">or electric motors</td></tr>
<tr><td>Capacity 750cc</td><td colspan="3"></td></tr>
<tr><td rowspan="2">Mopeds</td><td>Moped Conventional, Gasoline, biofuels</td><td colspan="3">Conventional, Euro I-V</td></tr>
<tr><td>Electric mopeds</td><td colspan="3">Pure electric technology</td></tr>
<tr><td rowspan="13">Light Duty Vehicles (<3.5 ton)</td><td>Gasoline</td><td colspan="3">Conventional, Euro I-V</td></tr>
<tr><td>Hybrid Gasoline</td><td colspan="3">LDV gasoline hybrid technology</td></tr>
<tr><td>Plug-in hybrid Gasoline</td><td colspan="3">Plug-in hybrid technology</td></tr>
<tr><td>Diesel</td><td colspan="3">Conventional, Euro I-V</td></tr>
<tr><td>Hybrid Diesel</td><td colspan="3">LDV diesel hybrid technology</td></tr>
<tr><td>Biofuels</td><td colspan="3">Biofuels</td></tr>
<tr><td>LPG</td><td colspan="3">LPG</td></tr>
<tr><td>CNG</td><td colspan="3">CNG</td></tr>
<tr><td>Synthetic fuels</td><td colspan="3">Synthetic fuels</td></tr>
<tr><td>Plug-in hybrid Diesel</td><td colspan="3">Plug-in hybrid technology</td></tr>
<tr><td>Battery electric</td><td colspan="3">Battery electric technology</td></tr>
<tr><td>Hydrogen</td><td colspan="3">Hydrogen fuel cell</td></tr>
<tr><td rowspan="5">Heavy Duty Trucks (> 3.5 ton)</td><td>Capacity 3.5-7.5 ton, Conventional</td><td rowspan="4">Diesel trucks</td><td rowspan="4">Methane trucks (LNG)</td><td rowspan="4">LPG trucks</td></tr>
<tr><td>Capacity 7.5-16 ton, Conventional</td></tr>
<tr><td>Capacity 16-32 ton, Conventional</td></tr>
<tr><td>Capacity >32 ton, Conventional</td></tr>
<tr><td>Capacity 3.5-7.5 ton, Hybrid</td><td colspan="3">Truck diesel hybrid technology , biofuels, synthetic fuels</td></tr>
</table>

Category	Type	Technology
	Capacity 7.5-16 ton, Hybrid	
	Capacity 16-32 ton, Hybrid	Electric trucks, Hydrogen fuel cell trucks
	Capacity >32 ton, Hybrid	
Buses-Coaches	Diesel	Conventional, Euro I-V
	CNG	CNG thermal
	LPG	LPG
	Buses only Hybrid Diesel	Hybrid Diesel technology
	Battery electric	Battery electric technology
	Biodiesel	Biodiesel technology
	Synthetic fuels	Synthetic fuels
	Hydrogen	Hydrogen fuel cell
Metro	Metro Type	Metro Technology
Tram	Tram Type	Tram Technology
Passenger Train	Locomotive	Locomotive diesel
		Locomotive electric
	Railcar	Railcar diesel
		Railcar electric
	High speed train type	High speed train technology
Freight Train	Locomotive	Locomotive diesel
		Locomotive electric
	Railcar	Railcar diesel
		Railcar electric

A.1.3 FORECAST-Tertiary

FORECAST Tertiary is a module of the FORECAST family developed by TEP Energy (TEP) and Fraunhofer ISI. As inherent to the FORECAST model family, the module is used to develop long-term scenarios for future energy demand and emissions. FORECAST Tertiary focuses on the buildings and appliances diffusion and energy consumption in the tertiary sector

The model has been developed and extended in recent years and has been applied in several studies. Jakob et al. (Jakob et al. 2012; Jakob et al. 2013) extended the static bottom-up model of Fleiter et al. (Fleiter et al. 2010) to present the coherent bottom-up model FORECAST Tertiary which allows for simulating the energy demand of the tertiary sector of the EU28+3 up to 2050 by country, by 8 sub-sectors, and by 17 end uses including lighting, electric heating, ventilation, cooling, refrigeration, cooking, data centers with servers and others.

With this model, the impact of novel technologies, energy efficiency - (EEM), building refurbishment and other more general measures (e.g., organizational measures), the impact of policies on the development of energy demand can be estimated, particularly by comparing different scenarios. FORECAST Tertiary is based on the concept of EEMs, which represent individual options that improve energy efficiency when diffusing through the equipment stock. Examples for electric appliances are fluorescent lamps, reduction of stand-by losses or changed user behavior. In terms of heating demand, the model represents the current building stock, the respective heating structure (fuel types) and its specific energy demand per building age, class and building typology. Consequently, policies are modeled by adjusting the dynamics and the level of diffusion of EEMs, or changes in the building code, depending on general and technology-specific economic parameters (e.g., investment costs or operation and maintenance costs).

The model adopts a bottom-up methodology which consists of a "sum product" of global drivers such as the number of employees and their specific floor area demand, specific energy service drivers (specific equipment or diffusion rates, e.g., share of cooled floor area, number of computers per employee) and specific energy consumption indicators (e.g., indoor temperatures). The latter consist of technical data on the end-uses such as installed power per unit of driver. Energy services, EEMs and their techno-economic description represent a key element of the modeling approach.

A.1.3.1 Calculation Approach

Electricity and or heating demand of a given year is determined as the product of the specific energy demand per unit of driver (e.g., number of computers, floor area cooled / ventilated, etc.), multiplied by the quantity of the given driver. The driver is further decomposed into an energy service driver (e.g., computers per employee, share of floor area ventilated/cooled, etc.) and a global driver (e.g., floor area or employees). The specific electricity demand is calculated as the product of installed (full load) capacity and the annual utilization rate (annual full load hour equivalent), whereas the heating demand is calculated based on the calculated useful energy demand per building type depending on geographic location and climate conditions. A schematic representation of the model structure is given in Jakob et al. (Jakob et al. 2012). As is usually the case in bottom-up simulation models, its dynamics is driven by time-dependent input variables. In the case of FORECAST Tertiary, dynamics is implemented by three sets of variables:

1. The dynamics of global drivers (called quantity structure) depends on general economic structural changes (number of employees by sub-sector) and on specific indicators (e.g., floor area per employee).

2. The dynamics of the energy service drivers such as the diffusion of cooled floor area is modeled by diffusion curves whose parameters depend on the past development, the sector and the energy service considered.
3. Specific energy demand varies over time due to the diffusion of new technologies and/or energyefficiency options (EEMs) or new building codes and refurbishment measures. The dynamics of the specific energy demand is modeled by initial starting values from which the relative impact of EEMs are subtracted. EEMs may reduce the installed power, the utilization rate, or both. Refurbishment measures on the building envelope allow for reduced useful energy demand based on reduced losses through the insulated envelope. For appliances, this approach allows for a more realistic consideration of the Ecodesign Directive's implementing measures (which often only address the installed power) and of other EEM (e.g., operational measures). EEMs diffuse into the building stock and the economic sub-sectors according to specific diffusion rates.

A.1.3.2 Sector Definition

The tertiary sector also referred to as the service or commercial sector comprises the NACE sub-sectors G to S (NACE rev. 2) as also shown in Table A.1-5 below. Energy demand of the tertiary sector includes building-related energy use of these sub-sectors and other energy use such as street lighting, ventilation of tunnels, public transport infrastructure and others. An exception is the sub-sector "Traffic and data transmission," where the transportation energy for trains, subways, trams etc. is – as is usual in energy economic analysis – not accounted for in the tertiary sector, but in the transportation sector.

Table A.1-5: Considered economic sub-sectors of the tertiary sector

Sub-sector	NACE 2	Description
Trade	G	Wholesale and retail trade
Hotel and restaurant	I	Hotels and restaurants, camping sites, mountain refuges, bars, canteens, catering
Traffic and data transmission	H, J	Transport (railway, road, water, air), storage and communication, cargo handling, post, telecommunications,
Finance	K	Finance and insurance
Health	Q	Health and social work, hospital activities, social work activities with accommodation
Education	P	Primary and secondary education, higher education, driving school activities

Sub-sector	NACE 2	Description
Public administration	O	Public administration and defense, compulsory, and social security
Other services	L,M,N,R,S	Other services (waste, sport, social services) + real estate and other services
Sub-sector	NACE 2	Description

A.1.3.3 Energy Service Drivers and Technology Data

Several energy services are defined for each of the sub-sectors. These energy services represent distinct appliances as well as building-related and other technologies which are responsible for the main share of the electricity demand in the tertiary sector (see Table A.1-6 for all the energy services considered in the model).

Most energy service drivers are related to the global driver, either representing floor area or the number of employees in the respective sub-sectors and countries (see Table A.1-6). For energy services that are assumed to be independent of these two global drivers (such as street lighting or cooking), only the energy service driver is used, and the respective technological parameters are chosen accordingly. It is assured that by using energy service drivers, the calculated energy consumption is based on a more realistic technological structure on a micro-level.

While heating is found in buildings across all sub-sectors, not all buildings of a given sub-sector are equipped with all the other energy services considered. Each energy service is related to the specific energy service driver. This energy driver represents a diffusion, penetration, or ownership rate of the respective technology in each of the sub-sectors. The data is explicitly differentiated between sub-sectors and countries. When implementing the described bottom-up modeling approach in the FORECAST model, new and existing buildings are also differentiated (as the incentives and costs for equipping new buildings are quite different from upgrading existing ones).

Table A.1-6: The energy services considered and their related energy service driver

Type	Energy service	Description	Energy service driver (D)	Related global driver (G)
El	Lighting	Lighting of different types of rooms (and building-related outdoor lighting)	Share of floor area with lighting	Floor area

Type	Energy service	Description	Energy service driver (D)	Related global driver (G)
El/Th	Ventilation and cooling	Ventilation and cooling of rooms and buildings	Ventilated and cooled floor area of buildings	Floor area
El	Circulation pumps and other heating auxiliaries	Energy-using technologies which transform the energy necessary for distributing fluids, e.g., circulation pumps, ancillary units such as pumps or blower fans in heating systems	Floor area of buildings	Floor area
El	ICT offices	PC, monitors, copy/print, etc.	ICT-infrastructure of one office employee	Number of employees
El	Data centers	Servers in data centers or IT rooms	No. of servers	No. of employees
Th	Hot water	Hot water and process heat (e.g., cleaning)	Floor area of buildings	Floor area
Th	Direct electric space heating	Fuel heating excluded, this energy service covers heat pumps and electric heating	Share of floor area with electric heating	Floor area
Th/El	Laundry	Laundry, particularly in the hotel and health sectors	No. of beds/guests	Number of employees
Th/El	Cooking	Cooking in restaurants, health sector, large office buildings	No. of meals, no. of beds/guests	Number of employees
El	Refrigeration/freezing	Cooling of products (particularly retail sector)		No. of employees
El	Miscellaneous building technologies	Mainly unspecified electrical appliances	Floor area of buildings	Floor area
El	Street lighting	Lighting of streets and roads	No. of light points	None
El	Elevators	Elevators to provide vertical transportation in buildings	No. of elevators	None

Note: El: specific electricity-based energy service (hardly substitutable); Th: thermal energy service (might be substituted by other energy types)

Typical examples of energy service drivers are:

- Share of ventilated floor area
- Share of floor area with space cooling
- Number and type of information and communication (ICT) devices per employee (e.g., personal computers)

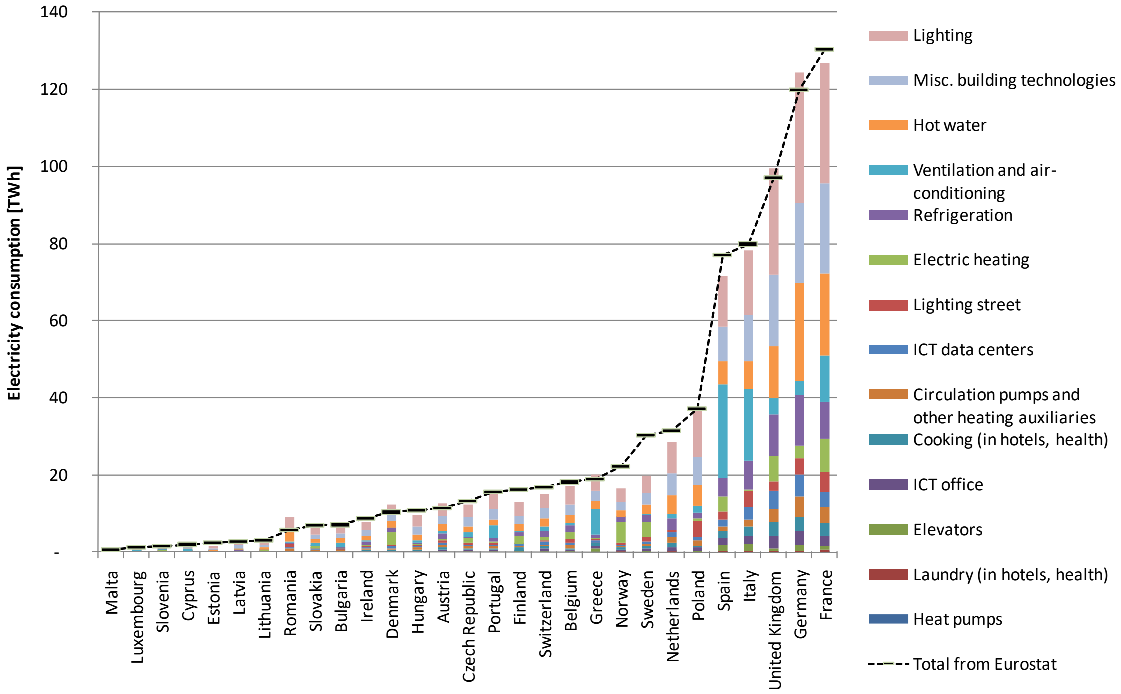
Each energy service in each sector is characterized by a specific energy demand. These specific demand values are the product of the installed specific capacity of a technology (e.g., W/m2) and its utilization in full-load hours per year. These values are explicitly differentiated between sub-sectors, countries and, whenever possible, implicitly between new and existing buildings and between already installed systems and those that are retrofitted.

Likewise, energy efficiency measures (EEMs) are described by their impact on both installed power and on the reduction of full load hours, e.g., through additional controls and building automation. Additionally, each of these EEMs is characterized by further techno-economic data such as specific investment and O&M costs. Thus, as describe in section 7.3.1 their diffusion of the EEMs depends on their cost-effectiveness.

A.1.3.4 Model Validation

Based on the calculation scheme, the total bottom-up energy demand for the tertiary sector is calculated and calibrated to the available statistical figures (e.g., Eurostat). Results are differentiated by either sub-sector or energy service (see Figure A1-16).

Figure A.1-16: Energy service share in total electricity demand by country (2015)

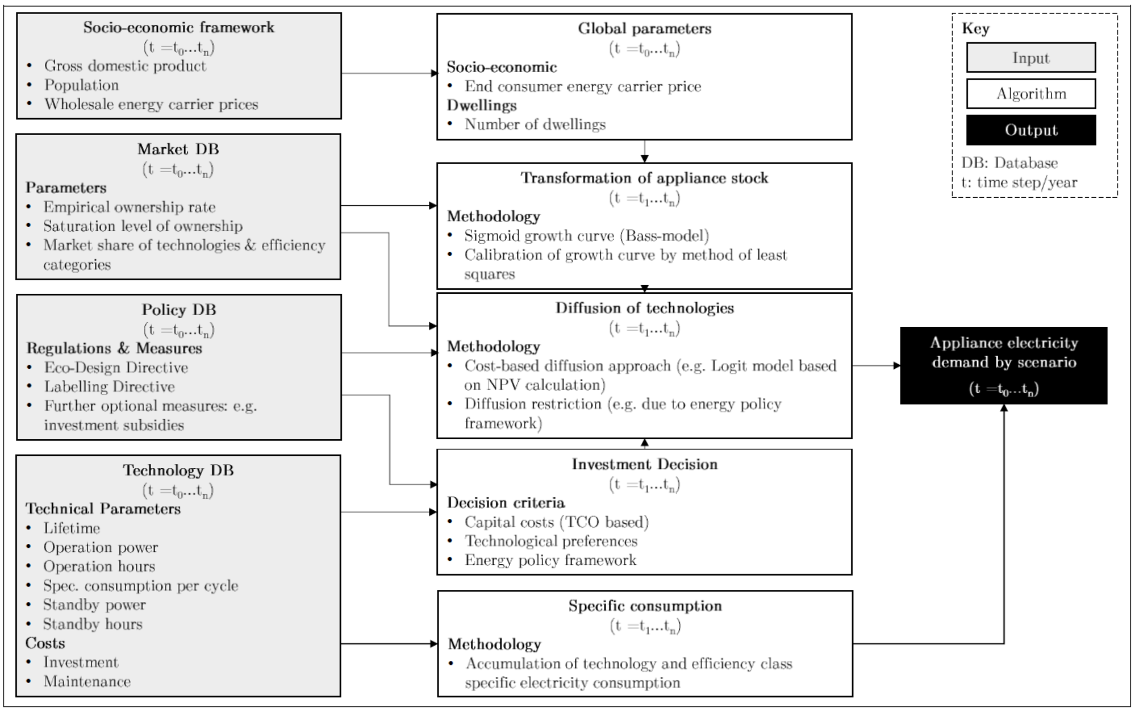


A.1.4 FORECAST-Appliance

FORECAST-Appliance is one module of the FORECAST model developed by Fraunhofer Institute for Systems and Innovation Research (ISI). The whole model is used to develop long-term scenarios for future energy demand. FORECAST-Appliance focuses on the appliances diffusion and energy consumption in the residential sector. It is a bottom-up techno-economic model with extensive technological details. Changes of socio-economic drivers (e.g., household number), energy carrier prices, and policy instruments (e.g., Eco-design and Energy Efficiency Labeling) are considered in the scenario definitions. An overview of the model is shown in Figure A.1-17. For detailed introduction, please refer to Elsland (2015)[6].

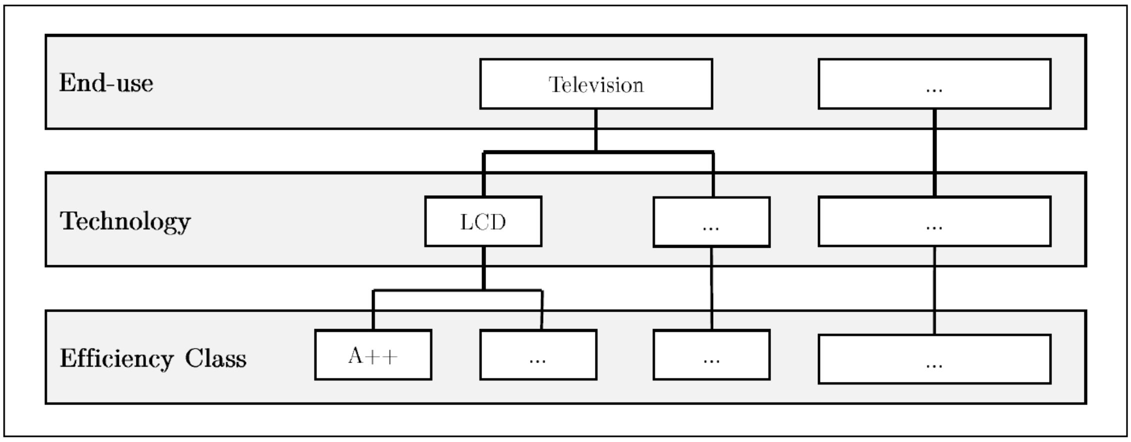
6 This doctor thesis introduces one of the three main modules of the FORECAST model, which is the FORECAST-Residential model. FORECAST-Appliance is a sub-model of FORECAST-Residential.

Figure A.1-17: Overview of the FORECAST-Appliance model



In FORECAST-Appliance, all the appliances of households are classified into four layers: (1) appliance group, (2) appliance, (3) appliance technology type, (4) appliance technology option. The coverage of first three layers is listed in Table 6. In the fourth layer, for each appliance technology type, there are 5 to 12 efficiency standards, each of which is represented by one appliance technology option. Figure A.1-18 shows an example of the second to fourth layers.

Figure A.1-18: Appliance layers in the FORECAST-Appliance model



The diffusion of appliances is modeled in three layers (Elsland, 2015):

- First, at the level of "appliance (2nd layer)", the diffusion process is modeled as "ownership dynamics" following the Bass model (Bass, 1969), extended by considering the "rivalry substitution" (Mahajan and Peterson, 1985) and "disposable income elasticity" (Horsky, 1990) effects.
- Second, for each appliance, the share of different "appliance technology types (3rd layer)" are exogenously calibrated based on empirical data, because there are much more factors that influence the choice of households between technology types, for example, between Lightbulb, Halogen Lamp, Energy Saving Lamp, Fluorescent Lamp, and LED.
- Third, at the level of "appliance technology options (4th layer)" households are modeled to choose between options based on the "utility", which is decided by (1) exogenously calibrated "alternative specific constant" of the appliance, and (2) annualized cost of the specific technology option. Then, with the utility of each option, the choice of households is modeled following the nested multinomial logit model (Train, 2002). The options with "higher utility (i.e., higher efficiency)" are chosen with higher probability.

As a result, fundamentally driven by the number of households, the energy consumption of the whole appliance stock is calculated by multiplying the calibrated operation hours and operation power. For some appliances, FORECAST-Appliance also considers their energy consumption in the "stand-by mode", including washing machine, drier, dishwasher, television, computer screens, set-top boxes, laptop computers, desktop computers, vacuum-cleaner (wireless), and coffee machine.

A.1.5 INVERT

The **building stock model Invert/EE-Lab** is a bottom-up model to simulate energy-related investment decisions in buildings focusing on space heating, hot water generation and space cooling. It is based on a highly disaggregated description of the building stocks in the different countries of the EU (+ Norway, Iceland, Switzerland, UK) including type of building, age, state of renovation, existing heating systems, user structure as well as regional aspects such as availability of energy infrastructure for e.g., district heating or natural gas on a sub-country level. It simulates investment decisions in the building shell and the heat supply and distribution systems via a combination of a discrete choice approach and technology diffusion theory. This makes it possible to study the influence of various side-conditions including policy measures on the decisions taken by the actors.

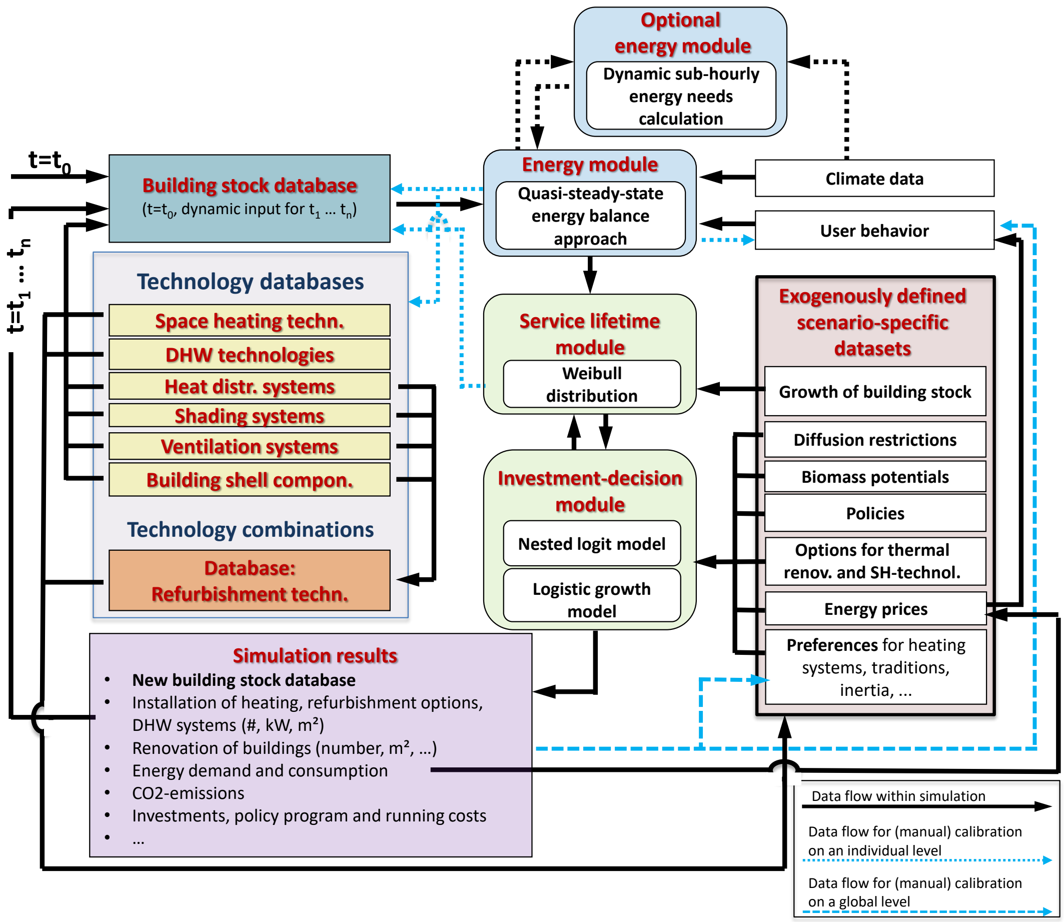
The Invert model has been developed and applied in national and international projects in the EU for more than 10 years now, many of them reflecting the entire EU building stocks (Invert/EE-Lab 2020).

A more detailed description of the model can be found below.

Invert/EE-Lab is a dynamic bottom-up simulation tool that evaluates the effects of different framework conditions (in particular different settings of economic and regulatory incentives) on the total energy demand, energy carrier mix, CO_2 reductions and costs for space heating, cooling and hot water preparations in buildings. Furthermore, Invert/EE-Lab is designed to simulate different scenarios (price scenarios, insulation scenarios, different consumer behaviors, etc.) and their respective impact on future trends of energy demand and mix of renewable as well as conventional energy sources on a national and regional level. More information is available on www.invert.at or e.g. in (Kranzl et al., 2013) or (Müller, 2012).

The basic structure and concept are described in Figure A.1-19.

Figure A.1-19: Overview structure of Simulation-Tool Invert/EE-Lab



Invert simulation tool originally has been developed by TU Wien/EEG in the frame of the Altener project Invert (Investing in RES&RUE technologies: models for saving public money). In more than 40 projects and studies for more than 30 countries, the model has been extended and applied to different regions within Europe, see e.g. (Kranzl et al., 2012), (Kranzl et al., 2013), (Biermayr et al., 2007), (Haas et al., 2009), (Kranzl et al., 2006), (Kranzl et al., 2007), (Nast et al., 2006), (Schriefl, 2007), (Stadler et al., 2007). The modification of the model in the year 2010 included a re-programming process and accommodation of the tool, in particular taking into account the inhomogeneous structure of decision makers in the building sector and corresponding distributions (Müller, 2010), (Müller, 2015).

The basic idea of the model is to describe the building stock, heating, cooling and hot water systems on highly disaggregated level, calculate related energy needs and delivered energy, determine reinvestment cycles and new investment of building components and technologies and simulate the decisions of various agents (i.e. owner types) in case that an investment decision is due for a specific building segment. The core of the tool is a myopic, multinomial logit approach, which optimizes objectives of “agents” under imperfect information conditions and by that represents the decisions maker concerning building related decisions.

Coverage and Data Structure

The model Invert/EE-Lab up to now has been applied in all countries of **EU-27 (+ GBR, NOR, CH, ISL).** A representation of the implemented data of the building stock is given at www.entranze.eu.

Invert/EE-Lab covers **residential and tertiary buildings.**

As efficiency technologies, Invert/EE-Lab models the uptake of different levels of renovation measures (country specific) and the diffusion of efficient heating and hot water systems.

Basic Approach and Methodology

The Invert/EE-Lab model

The core of the simulation model is a myopic approach, which optimizes objectives of agents under imperfect information conditions and by that represents the decisions concerning building-related investments. It applies a nested logit approach in order to calculate market shares of heating systems and energy efficiency measures depending on building and investor type. The following equation depicts the market share calculation as logit-model – in order to reduce complexity in the representation:

$$ms_{njb,t} = \frac{e^{-\lambda_b \cdot r_{njb}}}{\sum_{j=1}^{J} e^{-\lambda_b \cdot r_{njb}}}$$

$$r_{njb,t} = \frac{V_{njb,t}}{\sum_{j=1}^{J} ms_{njb,t-1} \times V_{njb,t}}$$

ms_{njb} = market share of alternative j in building b for investor type n at period t

r_{njb} = relative utility of alternative j in building b for investor type n

The model enables the definition of a various number of different owner types as instances of predefined investor classes: owner-occupier, private landlords, community of owners (joint-ownership), and housing association. The structure is motivated by the different perspectives regarding building related investments. For instance, energy cost savings are only relevant for those owners, which occupy the building. The corresponding variable relevant to landlords is a refinancing of energy savings measures through additional rental income (investor-tenant dilemma).

Owner types are differentiated by their investment decision behavior and the perception of the environment, the former is captured by investor-specific weights of economic and non-economic attributes of alternatives. The perception-relevant variables – information awareness, energy price calculation, risk aversion – influence the attribute values.

Outputs from Invert/EE-Lab

Standard outputs from the Invert on an annual basis are:

- Installation of heating and hot water systems by energy carrier and technology (number of buildings, number of dwellings supplied)
- Refurbishment measures by level of refurbishment (number of buildings, number of dwellings)
- Total delivered energy by energy carriers and building categories (GWh)
- Total energy needs by building categories (GWh)
- Policy program costs, e.g. support volume for investment subsidies (M€)
- Total investment (M€)

During the project Hotmaps (http://www.hotmaps-project.eu/), a methodology was elaborated to breakdown selected scenario results on a 100x100m raster cell level.

Moreover, Invert/EE-Lab offers the possibility to derive more detailed and other type of result evaluations as well. Based on the specific needs of projects and clients, other types of evaluations of the result data set are possible, e.g. in the format of different types of energy saving cost-curves (Toleikyte et al., 2018; Kranzl et al., 2016).

A.1.6 PRIMES-BuiMo

The PRIMES-BuiMo forms part of the PRIMES modeling suite and, more specifically, is one of the demand sub-models. It covers the residential and tertiary sectors and projects into the future the energy demand in these two sectors.

To this end, it follows a hybrid economic-engineering approach, combining the dynamics of the buildings' stock evolution with representation of idiosyncratic behaviors regarding the evaluation of technical options about renovation of the building's envelope and equipment choice (Fotiou, T. et al., 2019). The latter refers both to selection of fuel for each end use as well as to selection of technology vintage. Through the high level of detail in the representation of the decision-making process, the PRIMES-BuiMo allows assessing individual policies in a systematic manner: market and non-market barriers influence the choices and their removal is achieved by application of properly selected policies.

The core of the PRIMES-BuiMo combines discrete choice theory and dynamic programming for the decision-making process in energy-related investments in the buildings sector. More specifically, the decisions refer to:

- Demolition and construction of new buildings
- Renovation of the building's shell (rate and deepness)
- Equipment choice per use (fuel and technology vintage)

In the residential sector, 270 house classes are included depending on the age of construction (nine age bands covering 1920-2015), the type of building (single/multi-storey), the location (urban/semi-urban/rural) and the income classes (five categories). In the services sector, nine age bands cover period 1920-2015 and the segments considered are trade (commercial buildings, warehouses, cold storage), market services (private offices and other buildings in market services, hotels and restaurants), and non-market services (public offices, hospitals and health institutions, schools and educational buildings).

The renovation choice is performed among eight distinct renovation packages ranging from light to deep renovation, having an increasing impact on the achievable energy savings due to upgrade of the building's shell.

Individual energy uses per sector are defined as follows:

- Residential: space heating, space cooling, water heating, cooking and electric appliances (refrigeration, freezing, dish washers, washing machines, dryers, lighting, information & communication, entertainment, vacuum cleaners, ironing, small appliances)
- Services: space heating, space cooling, water heating, cooking, refrigeration, electric appliances, lighting

Equipment includes 50 different types for space heating, air cooling and other heat uses and 11 types of electric appliances (Figure A.1-7). The technology vintage of the equipment ranges from currently available technology to Best Not Available Technology, while learning-by-doing is exogenously defined and can vary per scenario. Scrappage of old equipment and appliances is considered along with premature replacement of equipment usually taking place in the choice of heating and cooling equipment after a deep renovation of the building.

Table A.1-7: Fuels and technologies for space heating & cooling, water heating, and cooking

	Space Heating
Diesel Oil	Conventional Boiler
	Condensing Boiler
Natural Gas	Conventional Boiler
	Condensing Boiler
	Micro-Cogeneration (CHP)
	Internal combustion engine
	Micro-CHP CCGT (Combined Cycle Gas Turbine)
	Micro-CHP Fuel Cell
	Gas Heat Pump (air to water)
	Autonomous Gas heater
Biomass	Wood Pellets Boiler
Electricity	Air-Source Heat Pump (air to water)
	Water Source Heat pumps (water to water/air)
	Ground-Source Heat Pump (brine to water/air)
	Electrical space heater
Solar	Thermal Solar
Steam	Distributed Heat
Geothermal	Geothermal Ponds
Solids	Stove for solid fuels
LPG	Autonomous LPG heater
	Stove for liquid fuels
	Space Cooling
Electricity	Air-Source Heat Pump (air to water)
	Water Source Heat pumps (water to water/air)
	Ground-Source Heat Pump (brine to water/air)
	Split system air condition
	Centralized cooling systems
Natural Gas	Gas Heat Pump (air)
	Absorption Chiller
	Adsorption Chiller
Steam	District Cooling

Water Heating	
Diesel Oil	Conventional Boiler
	Condensing Boiler
Natural Gas	Conventional Boiler
	Condensing Boiler
	Micro-CHP Internal combustion engine
	Micro-CHP CCGT
	Micro-CHP Fuel Cell
	Gas Heat Pump (air to water)
	Autonomous Gas heater
Biomass	Wood Pellets Boiler
Electricity	Air-Source Heat Pump (air to water)
	Water Source Heat pumps (water to water/air)
	Ground-Source Heat Pump (brine to water/air)
	Heat Pump Water Heater
	Simple electrical water heater
Solar	Thermal Solar
Steam	Distributed Heat
Geothermal	Geothermal Ponds
Solids	Stove for solid fuels
LPG	Autonomous LPG heater
Cooking	
Natural Gas	Gas Cookers
Biomass	Solid/Biomass Cookers
Electricity	Electric Cookers
LPG	Liquid Cookers

Source: Fotiou et al. (2019)

Key feature of the PRIMES-BuiMo is the way system-wide policy targets are handled. Policy signals are translated into appropriate inputs to the model: the obligation to reduce energy consumption is seen as a penalty factor on the cost of energy; the promotion of Energy Services Companies (ESCOs), the obligation of utilities to support energy savings at the costumer’s premises, financial support schemes are applied as a means to reduce perceived costs and technical uncertainties as well as increased access to funding; the eco-design directive is seen as penalty factors for existing technology and perceived cost factors for advanced technology.

The model comprises two main parts. The first one, covering the demand, starts with the projection of the useful energy demand into the future applying exogenous projections regarding the macroeconomic and demographic conditions as well as the prices to econometric functions. This procedure is performed separately for space heating & cooling, water heating, cooking, lighting, black and white appliances.

In the second part, the buildings' stock is projected into the future applying exogenous projections regarding the demolition rate, the adjustment pace to the optimal buildings' stock and the transfer of population.

Next, the renovation strategy is decided, i.e. the timing and deepness of renovation. It should be noted here that only renovation for energy savings is considered. Considering the actual and hidden costs as well as eventual subsidies per renovation strategy, a large number of dynamic strategies per building type is produced and several of them are retained, each one being assigned with a relevant frequency. This allows to capture idiosyncratic behaviors and heterogeneous building characteristics.

The second part of the model includes the energy production decisions, i.e. those referring to selection of equipment to cover the energy demand previously calculated. The heating & cooling equipment choice follows, based on a calculated net present value that includes hidden and perceived costs, income classes (through varied discount rate) and technology maturity factors. Here the choices are nested hierarchically following the sequence: equipment type then technology type then fuel type. For lighting and electric appliances, the formulation follows the eco-design regulations.

The total cost of energy per unit of useful energy covered as well as the energy efficiency value are finally produced, thus determining the cost of energy in a building. This information serves as input to a new iteration of the model until equilibrium is achieved.

A.1.7 GEM-E3

A.1.7.1 The Financial Sector

The representation of financial transactions and instruments in the general equilibrium modeling framework is not new (Capros & Karadeloglou (1993), Capros et al (1991), Bourgignon Branson and de Melo (1989), Tobin (1969)), whereas the 2008 financial crisis and its impact on the real economy revived the efforts in developing and applying CGE models that explicitly treat financial flows (Dixon et al (2014), Martin Cicowiez, C. G. M. (2010)). The latest version of the GEM-E3 model features the financial sector in detail and can assess the interlinkages between the financial sector and the real economy.

The representation of the financial sector in the GEM-E3 model starts from the complete accounting of the financial flows – transactions among economic sectors. This accounting allows to determine the flow of funds, the debt profiles and the composition of agents' disposable income. The base year financial position of each agent is calculated using the institutional transactions statistics (full sequence of National Accounts that include all secondary transactions like property income, income from deposits etc.). The net lending position of each agent is built from bottom-up data (all sources of income including dividend payments, interest rates, debt payments, bond interest rates etc.). Data regarding the structure of the bilateral debt by agent are constructed according to current account statistics and proxies using cumulative bilateral trade transactions. All the financial transactions are arranged in a financial SAM framework for each country that is represented in the model.

From a modeling perspective two additional economic sectors have been added (a world and a domestic bank) and six financial assets (deposits, time deposits, public bonds, corporate bonds, private loans and treasury bills). Banks collect savings from the economic agents in surplus and supply money at interest rates that clear the financial market (national or regional) while taking into account the risk premium and net credit position of each agent.

The banking system and private sectors are represented following an "assets-liabilities balance" approach. Assets-liabilities balance in the banking sector serves to evaluate the capacity of banks to lend to the private sector. Governments and firms issue bonds/bills to cover their deficit while households receive loans. Total public debt is updated dynamically by accumulating deficit/surplus. Public debt further influences interest rates and annuities which determine the net savings of the public sector. The behavior of households regarding the management of financial assets is based on a portfolio model which is derived by maximizing expected utility. Household allocates its disposable income to consumption and financial assets on the basis of expected yields.

All agents' decision to lend or borrow is driven by the market clearing interest rate. Through the use of alternative macroeconomic closures, different options are available for globally clearing endogenous interest rates, national interest rates and interest rates that are differentiated according to agent-specific risk premium and associated financial position. Money supply can be fixed with endogenously determined interest rates, can fluctuate across time, depending on capital capacity utilization, or adjusted at given interest rate following endogenous money supply (bank reserves adjusted as needed to accommodate loan demand at prevailing interest rates).

The inclusion of the financial sector improves the simulation capabilities of the model in the following aspects:

- It moderates the short-term stress on capital markets by allocating capital requirements over a longer period (long-term financing schemes/loans). This effect is particularly visible in scenarios where the economy transits to a more capital-intensive structure and any limited availability of financing capital implies that capital costs will always rise.
- It allows to simulate the role of carbon – funds in the implementation of ambitious energy and climate policies.
- It allows assessing socioeconomic impacts of investment projects characterized by different risk profiles performed by agents with different risk/debt profiles.

- It allows for a detailed budgeting of debt by agent while it takes into account the impact of debt accumulation and debt sustainability in the ability of agents to borrow.
- Endogenous computation of interest rates for different financial assets (deposits, bonds, household and business financing, etc.) and direct link of nominal variables to the real economy.
- Versatile financing options that correct market gaps (i.e., financing to low-income households through energy saving programs) and inclusion of financial repayment plans that allow to trace the interest payments in the future.

Recent studies using the GEM-E3 model illustrate the importance of the financial mechanism in simulating policies that lead to capital-intensive economic structures. In EC (2016), Paroussos et al. (2019a) and Paroussos et al (2019b), it is shown that timely availability and access to low-cost financing can be a game changer in the implementation of ambitious energy and climate policies.

A.1.7.2 Human Capital and Endogenous Skills Formation, Unemployment, and Multiple Households

A key issue for assessing the economic impact of decarbonization or other structural policies is whether the attempt to drive up investment will run up against capacity constraints, including both capital and labor constraints. In particular, the accurate representation of policy implications on the labor market requires a distinction among labor skills and their availability, as policy instruments would have differentiated impacts across skills and can potentially cause a mismatch between labor demand and supply for specific skills (i.e., a policy strongly promoting R&I should be complemented with increased human capital, as R&I activities require a high-skilled workforce). Conventional macro-economic models do not differentiate between skills or they exogenously project the number of skills and the size of the labor force and capture only the potential constraint of broad labor demand and supply imbalances.

In GEM-E3, labor demand by firms depends on cost minimization of their production function while labor supply is distinguished by skill and is modeled through an empirically estimated wage function (linking wages and labor supply) that allows for the existence of unemployment. A more likely source of labor constraint in a scenario involving substantial structural change is at skill level. The shift of labor demand to sectors requiring highly skilled labor (i.e. a shift from agriculture to industrial manufacturing or financial services) can potentially cause a mismatch between demand and supply for specific skills and a potential skill shortage. An important caveat in model-based employment projections is that they commonly assume that labor markets are fully flexible, meaning workers can easily migrate to new jobs (i.e., costless and instant skills transformation).

The human capital module in the GEM-E3 model allows households and firms to endogenously decide upon the optimal schooling-education years and on the optimal workforce training respectively. Household's decision to enter the labor market or acquire a skill (through additional education) depends on expected income (based on expectations on wages and unemployment rate by skill). The schooling decision of households concerns only certain age cohorts and allows to endogenously determine the participation rate and the supply of skills in the economy. The decision of firms to train their workers allows representing endogenous labor productivity growth through training. In this modeling approach, there is no mobility among skills but workers of the same skill are mobile across sectors.

Implication of policies is not evenly distributed across industries and households. For example, in the case of energy system decarbonization, the suppliers of new clean energy technologies and skills will benefit (wind turbine manufacturers or PV installers) whereas some industries will decline (coal mines) and social groups may experience "technology gaps" and "energy poverty". In order to capture the "inequalities" within households that certain policies may imply, the GEM – E3 model features for each country ten households that are distinguished by income class with different consumption patterns, different saving rates and different sources of income according to the allocation of labor skills by type of household.

The inclusion of multiple households and human capital improves the simulation capabilities of the model in a number of aspects:

- Identification of potential bottlenecks due to skills scarcity
- The availability of Human Capital and skills is essential to enable productivity growth induced by R&I and knowledge spillovers. Without sufficient human capital and provision of highly skilled labor (researchers, engineers, STEM), R&I expenditures perform poorly whereas the capacity of the economy to absorb knowledge produced elsewhere is low (limited knowledge spillover effects).
- Reflection of the social dimension of climate policies enabling the assessment of income inequality within and across countries and the identification of vulnerable regions or agents.

A.1.7.3 R&I and Knowledge Spillovers

The modelling of technological progress in GEM-E3 draws on the endogenous growth theory developed in Romer (1990) and Acemoglu (2001). Technological change in the model is endogenous deriving from spending in R&I. The potential of productivity improvement driven by R&I expenditures is based on learning curves (with learning rates derived from a comprehensive literature review). The model simulates innovation which leads to reduction in production costs in terms of each factor of production. GEM-E3 has been updated to the latest data on R&I obtained from the IEA, the OECD and the European Commission.

The GEM-E3 model differentiates between private and public R&D. Private R&D reduces the cost directly in the region and sector performing the R&D, while learning by doing and public R&D reduce technology costs globally. The R&I

capacity of countries is linked to the respective human capital availability. The productivity improvements and associated cost reductions occur once the investment decision is made and thus the gains from the learning effect occur with a one period lag (usually five years).

Knowledge spillovers are represented in the model as positive externalities leading to higher productivity of R&D expenditure. Some of the key factors affecting spillovers include: the geographical proximity, distance to the technological frontier, absorptive capacity, human capital, property rights policy. The conventional modeling of knowledge spillovers in CGE models is based on the exchange of efficient products/services through the bilateral trade transaction of countries. In GEM-E3, knowledge diffusion is based on a novel approach that includes technology transfer matrices based on patent citation data and is linked to the absorptive capacity of a sector/country, with data from the EU and national Patent offices.

Total factor productivity of each firm depends on R&I expenditures, learning by doing and knowledge spillover effects. All parameters related to the specification of endogenous productivity growth (learning by doing, learning by research, knowledge spillovers, human capital) are estimated using panel data analysis with cross-country data for the EU member states, China, USA, Korea, Japan and Russia for the period 2005-2016.

The inclusion of endogenous R&I decisions, knowledge diffusion and learning effects improves the simulation capabilities of the model in the following aspects:

- Ability to capture impacts on production costs through economies of scale and R&I specialization. Positive effects due to increase in productivity may create comparative advantages in domestic and international markets for firms.
- Induced R&D spending on technologies mitigates the cost impacts of a capital-intensive transition (i.e., energy system restructuring) and magnifies economic growth potential.
- Allows the model to consistently evaluate the impacts of innovation policies and targets for specific sectors and countries and assess alternative R&D portfolios in clean energy technologies.

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