# 1 Executive Summary

Welcome to the Joule report, a project by Terajoule that combines advanced modelling with cutting‑edge digital reporting to deliver an enhanced user experience for the European Union. This BETA‑level iteration showcases how a dynamic report can compress extensive energy system data into a navigable format, allowing users to explore charts and images both horizontally and vertically. AI‑powered visualisations respond to natural‑language prompts, generating custom charts on demand in about a minute, while users can engage with the Energy Snake game during processing. The report features animated methodology diagrams, flow maps, and standard bar and line charts, visualising supply‑demand balances across up to 15 nodes for hydrogen, electricity, methane and synthetic liquids, covering residential, tertiary, industrial and transport sectors, including electric‑vehicle behaviour. Weather, demographics and industrial activity are integrated at each node, and users can drill down to specific carriers, countries or categories, with the narrative aligned to the displayed visualisations. This executive summary introduces the capabilities and scope of the Joule digital report for the EU.

The Joule Models, developed by Terajoule Energy, deliver a comprehensive European energy analysis that spans the entire value chain, including electricity, hydrogen, methane, synthetic fuels, CO₂, and offshore wind networks. Leveraging state‑of‑the‑art tools such as PLEXOS, PyPSA, ANTARES and SAint, the model evaluates investment pathways aimed at achieving EU climate neutrality by 2050. The analysis adopts a multisectoral planning approach, integrating diverse energy sources and technological solutions to assess the resilience and sustainability of the future energy supply. Scenarios explore the interaction of electricity generation, hydrogen production, methane utilization, and synthetic fuel deployment, providing a holistic view of how these sectors can collectively meet the EU’s decarbonisation targets. The high‑level findings underscore the importance of coordinated investments across sectors to ensure a balanced, secure, and low‑carbon energy system for the European Union.

## 1.3 Purpose Summary

This chapter outlines the overarching purpose of Terajoule’s inaugural proprietary energy model, which serves as a foundational vision of Europe’s electricity system through 2050. The model establishes a baseline scenario that captures the current trajectory of generation capacity, demand patterns, and system flexibility, enabling stakeholders within Terajoule to benchmark future developments. By providing a consistent analytical framework, the model supports internal activities such as testing alternative energy pathways, guiding research and development initiatives, and training AI agents specialized in energy modelling. Moreover, it facilitates the generation of detailed hourly demand profiles that reflect projected economic growth and consumer behaviour, allowing users to explore a range of plausible future demand scenarios. In essence, this baseline model acts as the core reference point for all subsequent scenario analysis, model validation, and AI‑driven forecasting efforts related to the European energy landscape.

## 1.4 Sectors Modelled

### 1.4.1 Hydrogen

The hydrogen sector within the European Union is currently in a foundational planning phase, with its existing infrastructure primarily comprising Steam Methane Reformers (SMRs) and associated local distribution networks. These SMR facilities, which currently produce hydrogen, are slated for a complete phase-out by 2050, necessitating the development and construction of new hydrogen production infrastructure. The EU is actively engaged in a comprehensive planning process to develop its hydrogen ecosystem, recognizing its strategic importance in the future energy landscape.   
  
Hydrogen's role is rapidly expanding across multiple sectors. Industrially, it is becoming increasingly critical for applications in refineries, steel production, and the manufacturing of ammonia and methanol. The stable and consistent supply required by these industrial processes is anticipated to be secured through long-term contracts or dedicated electricity provisions. Beyond industrial uses, hydrogen is projected to play a significant role in replacing CO2-emitting primary energy sources in electricity generation, transport, and the production of synthetic fuels, thereby serving as a key component in the future energy mix.  
  
The future hydrogen system is envisioned to integrate several core components: electrolysers for producing hydrogen from water, dedicated hydrogen storage facilities, and dedicated renewable energy sources to power the electrolysis process. The topological design of the hydrogen system is being modelled to mirror that of the electricity system, requiring a nodal alignment to efficiently determine and manage electrolytic supply. Looking towards 2050, the potential for techno-economically viable extraction of white hydrogen from geological sources, for instance in countries like France, is also under consideration, contingent on the development of appropriate extraction methods.  
  
To drive this transition, the EU has established ambitious targets and launched significant initiatives. Notably, the European Commission has approved a €998 million scheme to support renewable hydrogen production in the Netherlands, targeting at least 200MW of electrolysis capacity by 2024, expanding to 500MW by 2025, and an overarching goal of 3-4GW by 2030. Concurrently, the EU has sanctioned €1.4 billion in subsidies for various hydrogen projects across the bloc, designed to advance clean energy technologies. Overall, the EU's Hydrogen Strategy outlines ambitious production targets of 6GW of electrolysis capacity by 2024, yielding up to 1 million tonnes of renewable hydrogen, and a substantial increase to 40GW capacity producing 10 million tonnes of renewable hydrogen by 2030. Additionally, the EU aims to import 10 million tonnes of renewable hydrogen annually by 2030 to meet anticipated demand. While concerns regarding the feasibility of these 2030 targets have been expressed, the European Commission remains committed to achieving them.

### 1.4.2 Electricity

The electricity sector in the European Union is undergoing rapid transformation, driven by decarbonisation, sector coupling and the integration of variable renewable energy sources. By the first half of 2024 wind and solar together supplied 30 % of the EU’s electricity, overtaking fossil‑fuel generation which fell to 27 %. This shift reflects accelerated deployment of renewable capacity and the impact of recent market reforms aimed at stabilising prices and encouraging low‑carbon generation. Decarbonising power generation is a core requirement for the EU’s 2050 carbon‑neutral target; projections indicate that by 2050 electricity generation will be almost entirely free of carbon emissions, with the majority of output coming from wind, solar and other variable renewables. The sector also supports indirect electrification pathways, providing electricity for hydrogen production and synthetic fuels, thereby linking power generation to broader energy demand. To balance the increasing share of intermittent renewables, the EU will need additional flexibility resources, including battery storage, demand‑side response and expanded grid infrastructure. The coupling of electricity with other sectors, notably transport and industry, is accelerating demand, reinforcing the need for a resilient, low‑carbon electricity system that can meet both direct and indirect electrification needs while maintaining system stability.

### 1.4.3 Methane

The EU methane sector is emerging as a pivotal element of the energy transition, bridging the decline of coal, lignite and oil with the expansion of renewables and hydrogen. As conventional fossil‑fuel extraction is scheduled to cease by 2050, natural gas will no longer serve as a primary source of methane, prompting a shift toward biomethane and other low‑carbon gas alternatives. This transition is quantified by the EU’s commitment to cut methane emissions by 30 % by 2030 relative to 2020 levels, a target embedded in the 2024 regulation that mandates measurement‑based monitoring, reporting and verification (MRV) and leak detection and repair (LDAR) for oil, gas and coal operations. The regulation, effective July 2024, also extends to imported fossil fuels, requiring compliance by 2027 and leveraging satellite monitoring for “super‑emitting” events.   
  
Cross‑sectoral impacts are evident across electricity, heating and hydrogen production. During periods of prolonged low wind and solar output – the so‑called dunkelflaute, typically lasting up to two weeks – methane‑derived electricity and hydrogen provide critical backup, sustaining supply security. Biomethane, produced from waste and agricultural residues, is projected to see a pronounced uptake as the EU decarbonises its gas system, reinforcing the role of gas infrastructure while reducing net emissions.   
  
The regulatory framework enhances transparency and accountability, driving technological innovation in emissions detection and contributing to broader climate objectives under the European Green Deal and REPowerEU plan. By tightening standards for both domestic and imported methane sources, the EU aims to improve air quality, public health and economic resilience, while positioning itself as a leader in global methane reduction efforts, exemplified by its role in the Global Methane Pledge which targets a 30 % cut by 2030 across more than 100 participating countries.

### 1.4.4 Offshore Hubs

The Offshore Hubs sector in the European Union is characterised by a nascent but rapidly expanding offshore electricity network that is intended to serve as a backbone for trans‑European power distribution. The European Commission’s offshore strategy outlines a voluntary 300 GW capacity ambition for the region, while member‑state commitments target 111 GW of offshore renewable generation by 2030 and between 281 GW and 354 GW by 2050. These figures provide a quantitative benchmark against which the current and planned offshore hub infrastructure can be assessed.  
  
The Offshore Network Development Plan (ONDP), produced by ENTSO‑E as part of the Ten‑Year Network Development Plan, translates the non‑binding agreements of January 2023 into concrete transmission equipment requirements and cost estimates. The ONDP emphasizes integrated on‑shore/off‑shore planning, cross‑border cost‑sharing, and the deployment of high‑voltage direct‑current (HVDC) links. It also highlights the need for coordinated investment in port facilities – estimated at €6.5 billion by 2030 – to support the assembly, installation, and maintenance of offshore wind farms.  
  
Technological innovation is a key driver: floating offshore wind is projected to reach 7 GW by 2030, extending development into deeper waters where fixed foundations are not feasible. HVDC technology underpins the envisioned hub architecture, enabling efficient long‑distance power transfer and facilitating hybrid projects that combine generation and transmission assets across multiple jurisdictions.  
  
Market‑design elements underpin the sector’s economic potential. Integrated planning mechanisms aim to align offshore hub development with environmental objectives and resource optimisation. Cross‑border coordination is codified in the revised TEN‑E Regulation, which provides a framework for shared financing and operational responsibilities. Investment stability is reinforced through revenue‑stabilisation tools such as Contracts for Difference, which are expected to lower financing costs and attract private capital.  
  
Overall, the offshore hubs sector is moving from a limited set of radial connections toward a more interconnected, high‑capacity grid that could distribute up to several hundred gigawatts of renewable power across the EU. The alignment of capacity targets, infrastructure investment, and regulatory mechanisms suggests a substantial economic upside, provided the planned transmission assets and supporting ports are realised on schedule.

### 1.4.5 Electric Vehicles

The electric vehicles (EVs) sector in the EU presents a complex dynamic within the electricity system, characterized by both significant load creation at the distribution level and the future potential for system balancing. Modelling of this sector primarily focuses on passenger electric vehicles, considering their unique operational patterns compared to other transport types like trucks and buses, which are anticipated to create a more predictable load. Passenger EVs are modelled considering diverse charging behaviors, including home charging, street charging, and office charging. A granular approach is taken to demand profiles, dissecting urban areas based on demographics and vehicle usage patterns, encompassing activities such as working from home, automated car sharing services, school runs, and evening activities.  
  
Current market trends in the EU indicate a notable shift towards electrification. As of June 2024, battery-electric vehicles (BEVs) constituted 14.4% of the EU car market, reflecting a steady increase in adoption. Hybrid-electric vehicles (HEVs) have also seen substantial growth, reaching 29.5% of the market share, while plug-in hybrids (PHEVs) experienced a decline to 6.1%. This growing penetration is supported by an expanding charging infrastructure, with new legislation mandating the installation of fast-recharging stations every 60 kilometers along major highways by 2025 across the EU.  
  
Technological advancements have further bolstered the attractiveness of EVs. The year 2024 witnessed improvements in battery efficiency and the introduction of a wider variety of vehicle models, including SUVs and city cars, catering to diverse consumer preferences. These developments are contributing to a broader shift in consumer preferences towards electric vehicles, driven by increasing public awareness and product availability. Regionally, adoption rates vary, with Northern and Western European countries such as Norway, the Netherlands, Germany, and France leading in EV uptake. Southern and Eastern European regions, including Catalonia in Spain and Lombardy in Italy, are progressively improving their adoption levels. The ongoing investment in charging infrastructure and continuous technological innovation in battery technology and vehicle design are essential factors underpinning the sector's evolution, enhancing both the efficiency and cost-effectiveness of electric mobility within the EU.

# 2 Modelling Methodologies

The high‑level architecture of the EU modelling framework is built around a unified spatial topology defined at the NUTS‑2 level, which partitions the Union into regions of comparable size and socio‑economic relevance. This common grid underpins all energy carriers, electricity (including offshore hubs), hydrogen, and electric vehicles, ensuring consistent inter‑regional linkages and facilitating integrated scenario analysis.  
  
Data ingestion begins with the latest transmission system data for each carrier. Electricity network topology and parameters are sourced from ENTSO‑E, hydrogen pipelines from ENTSOG, and complementary grid attributes from the SCI‑grid repository. These datasets are harmonised onto the NUTS‑2 mesh, creating carrier‑specific base grids that share node identifiers and adjacency structures.  
  
Offshore electricity infrastructure is modelled by attaching additional nodes to the coastal NUTS‑2 regions of each member state. While not every country activates offshore zones in a given scenario, the offshore node set remains in the model to allow investment decisions and capacity expansion analysis. Offshore hubs are linked to the on‑shore grid through dedicated interconnectors, with capacity limits derived from current offshore wind connection data where available.  
  
Hydrogen distribution follows the same NUTS‑2 topology, with pipelines mapped onto the existing electricity grid where co‑location is feasible. The model incorporates conversion facilities (electrolysers, power‑to‑gas units) at strategic nodes, enabling cross‑carrier flow of energy.  
  
The electric‑vehicle sector is represented as a demand and flexibility layer attached to the electricity nodes. Vehicle charging demand is allocated to NUTS‑2 regions based on population and vehicle registration statistics, while vehicle‑to‑grid (V2G) capabilities are modelled as distributed storage at the same nodes.  
  
Overall, the architecture provides a coherent, regionally granular platform that integrates multiple carriers, supports offshore investment modelling, and leverages authoritative data sources to reflect the current state of the EU energy system.

## 2.2 Modelling Approach

The modelling approach for the EU energy system is executed in a two‑stage optimisation framework. In the first stage, an expansion model determines the optimal capacity additions across electricity, hydrogen and transport infrastructures. Candidate technologies for electricity generation include utility‑scale solar PV, offshore wind (both fixed‑bottom and floating), onshore wind, small modular nuclear reactors (SMR) and battery storage at both utility and building levels. For hydrogen, the model can invest in methane pyrolysis or water electrolysers, as well as hydrogen storage facilities. It also decides on the construction of synthetic fuel production plants for kerosene and methanol, which are sized according to downstream hydrogen availability and captured CO₂ volumes. Electricity transmission assets are selected from the TYNDP scenarios, while hydrogen transport options comprise refurbishing existing methane pipelines or building new dedicated hydrogen pipelines; if a methane line is refurbished for hydrogen, its capacity is removed from the methane transport pool.   
  
The second stage is a dispatch model that uses the capacity portfolio from the expansion step as input to simulate hourly operation. This includes detailed representation of demand sectors, residential, tertiary, industry and transport, for each energy carrier. Each sector is linked to its respective market via a wheeling cost that captures taxes and congestion charges, guiding the model’s choice between utility‑scale and prosumer‑level investments. Electric vehicle fleets are modelled with vehicle‑to‑grid capabilities, allowing them to provide flexibility services.   
  
Because storage investments are often under‑represented in the expansion results, a post‑processing adjustment is applied to reinforce storage capacity where needed to ensure system adequacy. The combined two‑step process thus yields a cost‑optimal, sector‑coupled description of the EU’s future energy infrastructure, reflecting technology options, sectoral demand, and the interplay between electricity and hydrogen networks.

## 2.3 Data Sources

The model draws its input data for the European Union from a series of established scenario and infrastructure datasets. Baseline generation capacities, storage capacities and commodity price forecasts are taken from the TYNDP 2024 scenarios, which provide a comprehensive view of existing and planned electricity assets across the EU. Grid topology and investment candidates are sourced from the electricity TYNDP 2024, delivering both the current baseline grid configuration and the list of potential network upgrades. Since a hydrogen transmission network does not yet exist, the hydrogen grid is initialized at zero, with investment cost parameters derived from the European Hydrogen Backbone study, which outlines cost assumptions for a pan‑European hydrogen corridor. Information on the natural gas (methane) transmission system is obtained from the Sci‑grid and ENTSOG datasets, supplying network characteristics and cost data for the existing gas grid. Additional investment cost details are supplemented by the Danish Energy Agency’s Technology Catalogue, which provides technology‑specific cost data; where gaps remain, the model calculates missing costs and prices using standard engineering and economic assumptions. Together, these sources furnish a consistent and detailed set of inputs for the EU‑wide modelling exercise.

## 2.4 Sectoral Methodologies

### 2.4.1 Electricity

The electricity system in the EU is modelled as an integrated market that supplies four end‑use sectors: industry, transport, residential and tertiary. The reference grid serves as the baseline network, to which additional transmission candidates are added to represent potential expansions. Investment candidates include on‑shore wind, utility‑scale solar PV, offshore wind farms, nuclear small modular reactors (SMRs) for industry, and distributed generation such as rooftop solar with battery storage in residential and tertiary buildings. In the market‑based segment, larger generation plants, both renewable (on‑shore and offshore wind, solar PV) and nuclear, are assumed to be connected directly to the wholesale electricity market. By contrast, sector‑specific investments (e.g., rooftop PV with batteries) are placed within the demand side of the industrial, residential and tertiary sectors. Demand‑side response (DSR) is modelled for the tertiary and industrial sectors, reflecting flexible consumption that can be shifted in response to market signals.  
  
Grid expansion follows a candidate‑addition approach: the reference transmission topology is supplemented with optional lines and offshore hubs. Offshore zones are delineated along the European seas, each evaluated for its capacity to host wind farms and other offshore renewables. Offshore hubs act as collection points, aggregating power from multiple wind farms before transmitting it ashore via high‑capacity links. Investment cost modelling distinguishes capital expenditure (CAPEX) and operational expenditure (OPEX) for offshore wind farms, hub infrastructure, and associated transmission. Economic efficiency analyses identify the least‑cost transmission routes and hub locations for integrating offshore generation into the on‑shore grid.  
  
Battery storage is introduced as an explicit investment candidate. Utility‑scale batteries are allocated in the market segment, while prosumer‑level batteries are post‑processed based on the installed rooftop PV capacity to reflect higher penetration in residential and tertiary sectors. The deployment of residential and tertiary batteries is driven not only by technology cost and discount rates but also by macro‑economic factors such as GDP, subsidy levels, and the financial sophistication of end‑users. This multi‑criteria approach captures the observed tendency for higher battery adoption in wealthier regions and where policy incentives are stronger.  
  
The model does not enforce the European Commission’s 2050 target of 300 GW offshore capacity; instead, offshore build‑out emerges from the optimisation based on cost and grid integration constraints. Consequently, the resulting offshore capacity reflects the most cost‑effective configuration given the candidate set, rather than a predetermined target.  
  
Overall, the sectoral methodology for electricity in the EU combines a market‑centric representation of large‑scale generation with detailed, sector‑specific investment options, a candidate‑based grid expansion framework, and a nuanced treatment of battery storage that incorporates both economic and socio‑economic drivers.

### 2.4.2 Hydrogen

The European Union is actively engaged in a comprehensive planning process for hydrogen development, envisioning a pivotal role for this energy carrier in its decarbonization strategy. This includes the conceptualization and initial stages of the European Hydrogen Backbone (EHB), a dedicated infrastructure for hydrogen transport across the continent. The costing data for this backbone is drawn from the European Hydrogen Backbone report, informing the capital expenditure (CAPEX) and operational expenditure (OPEX) calculations in the investment stage model, where pipeline lengths directly determine these costs. The model features 110 nodes, representing key locations within this potential network, and allows for investments in various supply sources: Electrolysers for green hydrogen, Steam Methane Reformers, Methane Pyrolysis, and Ammonia Regasification Terminals.  
  
Investment decisions within the model are initially unconstrained by geography, allowing for allocation across Europe. These decisions are influenced by a 'willingness to pay' (WTB) factor, which economically reflects the cost of fuel supply disruptions. A higher WTB prioritizes regions with the most advantageous renewable potential and competitive Levelized Cost of Electricity (LCOE), such as southern Europe for solar and coastal or windy regions for wind power, thereby steering green hydrogen production towards optimal locations.  
  
The regulatory framework significantly shapes the hydrogen sector. The Renewable Energy Directive III (RED III), adopted in 2023, is central to this, raising the EU-wide renewable energy target to at least 42.5% by 2030 (with an aspirational 45%). A core component of RED III is the establishment of a dedicated framework for Renewable Fuels of Non-Biological Origin (RFNBOs), defined as liquid or gaseous fuels derived from renewable electricity, excluding biomass, which must achieve a minimum 70% greenhouse gas (GHG) reduction compared to fossil equivalents (e.g., 94 gCO₂eq/MJ). For hydrogen, this translates to a life-cycle GHG emissions savings threshold of approximately 3.4 kgCO₂eq/kgH₂.  
  
RED III sets binding quantitative targets for RFNBOs across key sectors. In industry, 42% of hydrogen consumed must be RFNBOs by 2030, escalating to 60% by 2035. Member States have some flexibility to reduce these targets by up to 20% under specific conditions related to their national contributions to the overall EU target and fossil hydrogen consumption. For the transport sector, RFNBOs must constitute at least 1% of total energy consumption by 2030, contributing to a broader combined sub-target of 5.5% for advanced biofuels and RFNBOs. To incentivize their uptake, RFNBOs receive multipliers towards these targets: 1.5 times for aviation and maritime sectors, and 2 times for all other transport modes. This is further reinforced by the ReFuelEU Aviation Mandate, which sets progressive blending requirements for Sustainable Aviation Fuels (SAF) at EU airports, including a specific sub-target for synthetic aviation fuels (e-SAF), which are RFNBOs, rising to 1.2% by 2030 and 35% by 2050. The model incorporates these demand drivers, as transport demand covers aviation, maritime, and heavy-duty vehicles.  
  
The sustainability of RFNBO production is ensured through strict criteria, outlined in delegated acts complementing RED III. The electricity used for RFNBO production must be considered "fully renewable," meeting "additionality" requirements (coming from new, unsubsidized renewable capacity, generally from 2028 onwards, with transitional exceptions) and "temporal-geographic correlation" (matching generation with consumption in time and location). The second delegated act provides a methodology for calculating the full life-cycle GHG emissions of RFNBOs, ensuring transparent verification.  
  
The scale of the EU's hydrogen ambition is reflected in significant infrastructure investment plans. The European Hydrogen Backbone is projected to require a total investment ranging from €80 billion to €143 billion, with annual operating costs estimated between €1.6 billion and €3.2 billion. Several Member States are contributing to this vision. For example, Spain’s total estimated gross investment for hydrogen infrastructure, including the H2Med pipeline and underground storage, is approximately €4.9 billion (€3.7 billion for H2Med, €1.2 billion for storage), with Enagás planning to invest €3.125 billion specifically in renewable hydrogen infrastructure by 2030. Spain has also secured €1.22 billion in aid for seven large hydrogen valleys/clusters, totaling 2,292 MW of electrolysis power. Austria targets 1 GW of electrolysis capacity by 2030, while Portugal aims for 2-2.5 GW. Bulgaria supports pilot projects yielding 55 MW of green hydrogen between 2022 and 2026 and targets hydrogen usage of 1,000 tonnes of oil equivalent by 2030, increasing to 9,000 toe by 2040. These national initiatives collectively underscore the extensive investment and capacity build-out required to meet the EU's hydrogen and RFNBO targets.  
  
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### 2.4.3 Methane

The methane sector in the EU comprises four principal end‑use categories: the market (industrial and commercial supply), residential heating, tertiary industry activities, and transport. The current system is largely fueled by biomethane, while a proportion of the gas entering the EU network originates from non‑EU sources that still contain conventional natural gas. Biomethane serves three main functions within the EU energy mix: it meets direct final‑energy demand for heating and process uses, it can be combusted for electricity generation, and it acts as a feedstock for steam methane reformers that produce hydrogen for downstream applications. The existing gas transmission and distribution infrastructure is capable of being retrofitted to transport hydrogen. If such a conversion were undertaken, the grid would cease to carry methane, restricting biomethane supply to localized distribution networks rather than the wider transmission system. Consequently, a hydrogen‑focused retrofit would fundamentally reshape the role of the methane grid, confining biomethane to regional or onsite applications while eliminating its presence in the broader transport network.

### 2.4.4 Electric Vehicles

The modelling of the Electric Vehicles (EV) sector within the European Union (EU) adopts a comprehensive approach to understand charging demand, infrastructure utilisation, and grid impacts. Passenger cars are a primary focus, modelled in two principal configurations: vehicles predominantly utilising Home Charging and those relying on Street Charging. This distinction is crucial for assessing diverse charging behaviours and infrastructure demands.  
  
Driving demand is quantified in kilometers driven. A granular approach is applied, disaggregating driving habits based on age demographics (child, teen, adult, senior) and a range of daily activities including School Run, Evening Activities, Daily Activities, Part Time Workers, Remote Workers, Evening Leisure, Night Life, Full Time Workers, and Taxi services. Each geographical node within the model incorporates bespoke driving profiles derived from the age split of its population, leveraging data from Eurostat. Car ownership rates, estimated per demographic group, are integrated as a weighting dimension to accurately scale demand.  
  
Charging infrastructure is categorised into Home Chargers, Street Chargers, and Work Chargers. Home chargers are typically connected to residential nodes, with a modelled capacity of 7kV, representing a common range between 3.3kV and 11kV. Tertiary and street chargers are rated at 22kV. Access points are defined such that vehicles configured for Home Charging connect exclusively to home chargers, while Street Charging vehicles access both street and work chargers. Charger availability is a critical factor, incorporating demographic groups such as Full time workers, part time workers, remote workers, university students, unemployed, and senior citizens, to determine when vehicles have access to charging facilities throughout the day.  
  
Specific rules govern charger access and sharing. For car owners utilising street chargers, a sharing ratio of one street charging station for every 20 vehicles is applied. In office environments, a ratio of one charging station per 40 vehicles is considered, with full-time and part-time workers having access to work chargers from 08:00 to 20:00. General access permits vehicle owners to connect to their respective chargers when not engaged in work, educational pursuits, or other activities away from home. In terms of capacity, it is assumed that work chargers can accommodate 25% of the maximum number of EVs that could connect, street chargers can accommodate 50%, and home chargers are assumed to be sufficient for 100% of electric vehicles configured for home charging.  
  
The modelling framework integrates both baseline and projection data. Baseline data encompasses the current number of EVs, their existing usage patterns, and the present charging infrastructure landscape. Projection data incorporates estimations for future EV adoption growth, anticipated advancements in battery technology, and the projected expansion of charging networks. The analysis further considers distinct charging behaviours, including Residential Charging (typically during evening and night hours), Public Charging (which varies based on availability and user behaviour), and Fast Charging, assessing its impact on quick top-ups and peak demand periods. The overall grid impact of EV charging, including contributions to peak loads and potential needs for grid reinforcements, is assessed. Advanced considerations include the potential for Demand Response strategies, where EV charging can be adjusted based on grid conditions and electricity prices, and the modelling of Vehicle-to-Grid (V2G) technologies, where EVs could feed electricity back into the grid during high-demand periods.

# 3 Demand

The Demand section opens by outlining the current market demand across the European Union, emphasizing overall consumption patterns, growth trajectories, and the contribution of key sectors. Recent data show that total demand within the EU has continued to expand, driven primarily by increased consumption in the services and manufacturing sectors. Growth rates remain positive, with year‑on‑year increases observed in most member states, reflecting robust economic activity and rising consumer confidence. Demand is notably higher in the core economies, where per‑capita consumption outpaces the EU average, while peripheral regions exhibit more modest growth. Sectoral analysis indicates that high‑technology goods and renewable energy solutions are experiencing the strongest demand surges, whereas traditional commodities show steadier, incremental growth. Overall, the EU’s demand landscape is characterized by sustained expansion, diversified sectoral contributions, and regional variations that together shape the market dynamics.

## 3.2 Annual Demand

### 3.2.1 Energy Demand

#### Austria

The 2050 annual energy demand for Austria (AT) is characterised by a dominant share of electricity across all sectors, complemented by substantial hydrogen use in industry and transport, modest methane contributions, and a residual amount of liquid fuels confined to aviation. In the industrial sector, electricity accounts for approximately 59.7 TWh, hydrogen 28.9 TWh and methane 13.0 TWh, reflecting the sector’s reliance on electrification where feasible and hydrogen where high‑temperature processes persist. The building sector shows electricity consumption of about 6.92 TWh (appliances and heating/cooling) and direct heat of 8.2 TWh, with methane supplying roughly 1.5 TWh and liquids negligible. Households consume 9.34 TWh of electricity (appliances 9.23 TWh, cooling 0.11 TWh) and 19.32 TWh of heat for space‑heating and hot‑water, together representing the reported total household demand of 41.9 TWh; bio‑fuels contribute around 0.5 TWh. Transport is overwhelmingly electrified at about 21.5 TWh, while liquids are used almost exclusively for international aviation (7.8 TWh). Hydrogen appears in heavy‑duty freight and some rail and shipping applications totalling roughly 1.2 TWh, and methane is limited to shipping (≈0.03 TWh). Summarising the four final energy carriers considered in the model, Austria’s projected 2050 demand consists of roughly 97.5 TWh of electricity, 30.1 TWh of hydrogen, 14.5 TWh of methane and 7.8 TWh of liquid fuels. This carrier distribution underscores a clear transition toward electricity‑centric energy provision, with hydrogen serving as a targeted complement for sectors where direct electrification remains challenging, and fossil‑derived liquids and methane relegated to niche roles.

#### Belgium

Belgium's projected annual energy demand for 2050 reflects a significant transformation in its energy landscape, marked by a pronounced shift towards electrification across key sectors. The analysis considers final energy demand for electricity, hydrogen, methane, and liquids, consistent with the TYNDP 2024 demand figures, which utilize an energy transition model with adjustments to align with future trends.  
  
Industry is projected to be the largest consumer, with an approximate total demand of 227.47 TWh. Energetic demand within this sector, totaling 140.21 TWh, is predominantly met by electricity (89.97 TWh), with methane and hydrogen also playing roles. Major industrial subsectors contributing to this demand include Chemicals, 'Others', Steel, and Datacenters. Non-energetic demand, amounting to 87.26 TWh, is primarily covered by liquids (43.73 TWh), hydrogen, and biofuels, with the Chemicals subsector being the dominant consumer. Specifically, in industrial applications, electricity is centric, notably in 'Others' (26.96 TWh), chemicals (24.46 TWh), and datacenters (15.99 TWh). Hydrogen appears modestly, chiefly in steel (12.09 TWh) and chemicals (1.11 TWh).  
  
Transport is anticipated to consume about 140.5 TWh. While traditional liquid fuels (62.9 TWh) and methane (43.6 TWh) remain dominant, particularly in international aviation and maritime transport (e.g., ~18.9 TWh for aviation and ~43.3 TWh for international shipping), electricity plays a significant and growing role, accounting for 32.3 TWh. This electrification is particularly evident in road transport, with cars (20.84 TWh) and trucks (7.58 TWh) largely electric. Hydrogen is also emerging in this sector, primarily in trucks (1.28 TWh) and passenger trains (0.045 TWh).  
  
The Buildings and Households sectors show comparable demands, heavily reliant on electricity. The Buildings sector requires roughly 28.90 TWh, with electricity largely supplying appliances (22.50 TWh) and space heating/hot water (5.88 TWh). Methane contributes 6.70 TWh for appliances, while heat and liquids represent smaller portions at 1.78 TWh and 1.70 TWh respectively. The Household sector demands approximately 27.70 TWh. Of this, about 81% is supplied by electricity, with heat contributing around 10%, methane 6%, and biofuels 3%. Key end-uses in households include space heating, appliances, and hot water, predominantly met by electricity.  
  
Overall, the 2050 energy landscape for Belgium indicates substantial electrification in residential and commercial buildings, alongside a growing importance of electricity and hydrogen in transport and industry. While traditional liquid fuels and methane persist in specific industrial non-energetic uses and hard-to-abate transport segments like aviation and international shipping, their overall share in the energy mix is projected to be secondary to electricity in many areas. Due to the lack of comparable 2019 baseline data, a quantitative year-on-year trend cannot be established; however, the 2050 snapshot suggests an advanced state of electricity penetration in Belgium, particularly in buildings, households, and road transport.

#### Bulgaria

In 2050, Bulgaria's projected combined final energy demand across the Industry, Households, Buildings, and Transport sectors is approximately 69.2 TWh. This demand is distributed among key energy carriers including electricity, hydrogen, methane, and liquids, with other sources like heat and bio-fuels playing significant roles in specific sectors. The analysis of this demand is derived from the TYNDP 2024 demand figures, employing an energy transition model and incorporating insights from European TSOs.  
  
The \*\*Industry\*\* sector is projected to be the largest consumer, accounting for 36.23 TWh of the total energy demand. Energetic uses comprise 30.22 TWh, where electricity is the dominant carrier at approximately 13.5 TWh. Hydrogen follows as a significant energetic carrier at around 7.5 TWh. Bio-fuels and methane contribute secondarily, with approximately 2.5 TWh and 2.2 TWh respectively, while heat and solid fuels play only marginal roles. Non-energetic uses within industry account for 6.01 TWh, primarily driven by hydrogen for fertilizers (estimated at 3.7-3.87 TWh) and liquids for other subsectors, contributing around 2.0 TWh.  
  
Following Industry, the \*\*Transport\*\* sector is expected to demand 13.72 TWh. Electricity is a primary carrier for road vehicles, with one source indicating 7.35 TWh (53.6% of the sector's total) and another estimating its contribution at roughly 8.5 TWh across various modes. Liquids remain essential, particularly for international aviation (1.98 TWh) and shipping (0.245 TWh), totaling around 2.9-3.65 TWh. Hydrogen is also significant, especially for trucks (1.29 TWh) and rail (approximately 0.066 TWh), contributing an overall 1.38 TWh to the sector. Methane is utilized in buses, trucks, and a small share of shipping. Within this sector, cars are projected to consume 5.76 TWh and trucks 2.89 TWh, considering all carrier types.  
  
\*\*Households\*\* are projected to require 13.02 TWh. Space heating and hot-water are major demands, consuming 5.93 TWh and 3.67 TWh respectively. Electricity and heat are key sources for these functions; electricity accounts for 2.25 TWh for space heating and 1.59 TWh for hot-water, while heat provides 2.44 TWh for space heating and 1.35 TWh for hot-water. Appliances are largely powered by electricity (2.67 TWh), and cooling demand is met predominantly by electricity (0.19 TWh). Bio-fuels and methane contribute modestly to household energy needs.  
  
The \*\*Buildings\*\* sector is anticipated to have a demand of 6.23 TWh. Appliances dominate this demand, accounting for 4.68 TWh and being predominantly supplied by electricity (approximately 4.257 TWh). For space heating, hot-water, and cooling, electricity contributes around 0.58–0.73 TWh for each function, with heat also being important for heating requirements. Methane, bio-fuels, and liquids account for smaller shares in this sector.  
  
Across all sectors, electricity emerges as the most widely utilized carrier in Bulgaria's 2050 energy landscape, particularly prominent in industry, households, buildings, and road transport. Hydrogen is developing into a notable secondary carrier, especially within industry and transport. Bio-fuels and methane maintain specific, albeit smaller, roles, while heat is crucial for residential heating but has limited application in industry. Liquids are predominantly confined to international aviation and maritime transport.  
  
It is important to note that a direct comparison of energy demand changes between 2019 and 2050 for Households, Buildings, and Transport is not possible due to the absence of 2019 data for these specific sectors. Furthermore, the available dataset is limited to Bulgaria, precluding a direct comparative analysis with other European countries to evaluate variations in carrier reliance or strategic differences.

#### Croatia

Annual energy demand for Croatia in 2050, as projected through the TYNDP 2024 demand figures and the energy transition model, highlights specific carrier reliance across key sectors. These projections are developed in coordination with the Transmission System Operators (TSOs) of European Union countries, originating from a distributed energy scenario with subsequent adjustments to align with future energy trends. The final energy demand considers a range of carriers, including hydrogen, electricity, methane, and liquids, alongside heat and biofuels where relevant.  
  
In the Buildings sector, total appliance consumption is projected at 3.58 TWh, primarily met by electricity at 3.01 TWh. Cooling demand is exclusively electricity-based, accounting for 0.25 TWh. Space heating and hot water collectively demand 1.08 TWh, with heat contributing 0.404 TWh and electricity 0.311 TWh. Methane, biofuels, and liquids play secondary roles in fulfilling the remaining heating and hot water needs within this sector.  
  
The Households sector demonstrates distinct consumption patterns. For space heating, electricity is a significant carrier at approximately 1.77 TWh (or 1.78 TWh), alongside comparable shares from heat (1.81 TWh) and biofuels (1.77 TWh), and methane contributing 0.97 TWh. Cooling demand is entirely met by electricity, requiring 0.67 TWh. Hot water consumption totals 3.12 TWh, with electricity accounting for 0.95 TWh of this, complemented by a mix of methane, heat, and biofuels. Household appliances predominantly rely on electricity, with a demand of 1.87 TWh.  
  
The Industrial sector is projected to have an approximate total demand of 17.82 TWh. Electricity serves a substantial portion of this demand at 5.46 TWh. Hydrogen is a crucial carrier, with a total demand of 6.25 TWh, split between 1.39 TWh for energetic uses and 4.86 TWh for non-energetic applications, notably in fertilizers and chemicals. Methane also plays a significant energetic role, demanding approximately 2.45 TWh. Liquids and biofuels contribute modestly to the overall industrial energy consumption, particularly within non-energetic demands alongside hydrogen and methane.  
  
Finally, the Transport sector is expected to require about 11.87 TWh. Electricity emerges as the largest carrier, demanding 5.42 TWh, primarily for cars. Liquids are also highly significant, accounting for 5.12 TWh, largely for trucks and international aviation. Methane contributes 1.21 TWh to transport needs, with hydrogen making a smaller contribution of 0.11 TWh. It is important to note that this analysis is based on a 2050 snapshot for Croatia, and the absence of 2019 data precludes a direct year-on-year comparison or a comprehensive assessment of cross-country variability.

#### Cyprus

In 2050 Cyprus is projected to have a total final energy demand of roughly 15 TWh, distributed across the four main sectors of Buildings, Industry, Households and Transport. The Buildings sector accounts for about 1.76 TWh, of which electricity supplies the dominant share (approximately 71 % or 1.25 TWh) while heat (thermal energy) contributes around 0.12 TWh for space‑heating and hot‑water needs. The Industry sector demands roughly 1.65 TWh, driven largely by the “Others” subsector (≈1.09 TWh) and with electricity again being the primary carrier (≈1.23 TWh). Household consumption totals about 2.5 TWh; electricity powers appliances, space‑heating, cooling and other end‑uses, whereas hot‑water demand relies on heat, amounting to 0.916 TWh. Transport dominates the overall demand with an estimated 9.6 TWh, of which electricity provides the single largest carrier contribution at 3.44 TWh (44 % of transport demand) and liquid fuels (oil‑derived) remain the second‑largest carrier, accounting for 4.27 TWh or 55 % of transport energy use. Hydrogen and methane each represent less than 1 % of the total energy consumption, appearing marginally in specific industrial processes and in niche transport applications such as trucks, ships and aviation. Biofuels are present only in trace amounts across all sectors. Overall, the future energy mix for Cyprus is heavily electricity‑centric, with the transport sector still reliant on liquid fuels, while emerging carriers such as hydrogen and methane play only a marginal role.

#### Czech Republic

In 2050 the Czech Republic’s annual final energy demand amounts to roughly 205 TWh across all sectors, distributed among the four main carriers considered in the model – electricity, hydrogen, methane and liquids. Households account for about 30 TWh, with electricity dominating space‑heating (12.3 TWh), hot‑water (4.6 TWh) and appliances (5.4 TWh). Methane and bio‑fuels provide secondary heating support, contributing roughly 1.5 TWh combined.  
  
The building stock (non‑residential) consumes approximately 16.9 TWh, of which electricity supplies two‑thirds (≈11.2 TWh, 66 %), methane about one‑fifth (≈3.5 TWh, 21 %) and direct heat the remaining 13 % (≈2.25 TWh). Bio‑fuels and liquid fuels are negligible in this sector.  
  
Industry is the largest single consumer with an energetic demand of about 93.3 TWh. Electricity remains the leading carrier (≈41.6 TWh, 44 % of industrial use), followed by hydrogen (≈23.7 TWh, 25 %) and liquids (≈13.0 TWh, 14 %). Methane contributes around 9.5 TWh (10 %). Within industry, the chemicals subsector is especially hydrogen‑intensive, accounting for roughly 27.3 TWh of non‑energetic demand that is largely supplied by hydrogen and liquid fuels. The steel sector uses a mix of electricity, methane and hydrogen totalling about 16.1 TWh.  
  
Transport demand reaches about 27.8 TWh, with electricity again dominant (≈18.7 TWh, 58 %). Liquid fuels, primarily for aviation, represent the second largest share (≈6.1 TWh, 19 %). Hydrogen is used mainly in heavy‑duty trucks and rail (≈2.6 TWh, 9 %), while methane plays a minor role (≈0.5 TWh, 2 %). Cars alone account for 10.7 TWh of electricity consumption.  
  
Aggregating across sectors, electricity constitutes roughly 69 % of the total final energy demand (≈141 TWh), hydrogen about 12 % (≈24 TWh), liquids 7 % (≈15 TWh) and methane 7 % (≈14 TWh). The remaining share is covered by bio‑fuels and direct heat. These figures reflect the strong electrification trend in the Czech energy system by 2050, with hydrogen emerging as a significant carrier in industrial processes and certain transport applications, while methane and liquids retain niche but essential roles.

#### Denmark

In 2050, Denmark's projected annual energy demand reflects a distinct transition across key sectors, as detailed by the TYNDP 2024 demand figures, which leverage an energy transition model developed in coordination with European TSOs. While the scenario originates from a distributed energy perspective, adjustments have been made to align with future trend views. The analysis focuses on final energy demand for carriers such as hydrogen, electricity, methane, and liquids, highlighting sector-specific dependencies and the overall energy landscape. A key limitation for trend analysis is the absence of 2019 comparative data within the provided extracts.   
  
The \*\*Household\*\* sector in Denmark is anticipated to have an overall energetic demand of 23.53 TWh by 2050. Heat emerges as the predominant carrier within this sector, accounting for 16.99 TWh, primarily dedicated to space heating and hot water supply. Electricity contributes a significant 6.54 TWh, covering various household appliances and other electrical needs.   
  
The \*\*Building\*\* sector's energy demand also underscores the importance of thermal energy. Heat supplies 2.58 TWh for space heating and hot water. Electricity is the principal carrier for cooling, requiring 0.22 TWh, and for appliances, demanding a substantial 5.96 TWh. An additional 0.17 TWh of electricity is used for space heating and hot water, while minor amounts of methane, biofuels, and liquid fuels supplement the sector's energy mix.   
  
The \*\*Industrial\*\* sector is projected to have an energetic demand of approximately 18.9 TWh. Electricity is the leading energy carrier, accounting for 10.4 TWh, representing roughly 55% of the sector's energetic demand. Methane follows as the second largest carrier with 6.8 TWh, approximately 36%, while hydrogen constitutes a modest 1.4 TWh, or about 7% of the energetic demand. Non-energetic demand, primarily from liquids, is estimated at around 1.2 TWh. The 'Others', Food, and Datacenters subsectors are identified as the largest contributors to industrial demand.   
  
For the \*\*Transport\*\* sector, the total energy demand is estimated at 28.8 TWh, demonstrating a strong electrification trend. Electricity is the most utilized energy carrier, totaling 13.08 TWh, predominantly for road vehicles, with cars alone accounting for 7.37 TWh entirely from electricity. Trucks also show a significant reliance on electricity. Liquids represent 8.69 TWh of demand, with international aviation being the largest segment at 8.53 TWh. Hydrogen plays a notable role, with a demand of 4.49 TWh, primarily for trucks (3.73 TWh) and ships (0.76 TWh). Methane also appears in international shipping, demanding 2.54 TWh.   
  
Across all sectors, electricity is positioned as the primary carrier for high-tech applications and mobility solutions, including road transport and parts of the industrial sector. Heat remains indispensable for ensuring residential and building comfort functions. Fossil-derived carriers such as methane and liquids are largely confined to specific, harder-to-decarbonize niches, notably heavy industry and international shipping and aviation. The comprehensive picture for 2050 in Denmark illustrates a strategic shift towards electrified and hydrogen-based energy systems, while thermal energy sources continue to fulfill essential comfort-related demands.

#### Estonia

Estonia's (EE) projected annual energy demand for 2050, as derived from the TYNDP 2024 demand figures and an energy transition model developed in coordination with European TSOs, illustrates a distinct distribution across various sectors and energy carriers. This scenario, rooted in a distributed energy approach with specific adjustments to align with broader future trends, considers the final energy demand for hydrogen, electricity, methane, and liquids, alongside significant contributions from heat and biofuels. The data primarily allows for an internal analysis of Estonia's energy landscape, as comparable 2019 data or cross-country benchmarks are not available for year-over-year or direct inter-country comparisons.   
  
In the household sector, the total energy demand for 2050 is predominantly met by heat and electricity. Direct thermal energy (heat) is the primary carrier for space heating (2.34 TWh) and hot water provision (1.22 TWh). Electricity largely fulfills the demand for appliances (1.37 TWh) and almost entirely for cooling (0.0008 TWh), signifying a strong electrification trend for these services. Biofuels and methane play only marginal roles in this sector.   
  
The non-residential building sector's total consumption is approximately 3.55 TWh. Similar to households, direct heat leads for space heating, accounting for approximately 61% of the heating demand, followed by electricity at around 31%. Methane holds a modest share of about 7% for heating. Appliances in this sector are overwhelmingly electricity-driven, comprising approximately 88% of appliance use, and cooling loads are fully electric.   
  
Industrial energy demand in Estonia for 2050 is diverse, distributed across subsectors such as Chemicals, Food, Metals, Paper, Datacenters, and 'Others', with the latter being the largest consumer. Electricity emerges as the primary energy carrier across most industrial subsectors. Hydrogen, biofuels, and methane appear as important secondary carriers. Notably, the 'Others' subsector exhibits a comparatively balanced mix, with electricity at approximately 1.16 TWh, hydrogen at about 0.68 TWh, biofuels around 0.98 TWh, and methane at roughly 0.15 TWh. Liquids are present in industry only in non-energetic forms.   
  
The transport sector's total energy demand is estimated at 4.8 TWh. Liquids dominate the transport mix, accounting for approximately 2.15 TWh, primarily driven by international aviation, shipping, and road vehicle fuels. Electricity is the second-largest carrier in transport, at approximately 1.87 TWh, mainly used in cars, buses, and vans. Methane and hydrogen also contribute to the transport mix, with methane at about 0.55 TWh and hydrogen at approximately 0.25 TWh, the latter being particularly relevant for trucks, freight trains, and ships.   
  
Cross-sectoral patterns indicate that electricity is set to become the leading energy carrier for indoor energy services (heating, hot water, appliances, cooling) and for an increasing share of industrial and transport activities. Direct heat remains essential for space heating in both residential and non-residential buildings. Liquids retain their dominance within the transport sector, particularly for long-distance and international modes. Hydrogen and biofuels are emerging as supplementary carriers, demonstrating their most notable presence in industry and specific transport subsectors. This comprehensive overview highlights a significant electrification trend across most sectors in Estonia by 2050, a persistent role for liquids in transport, and a growing diversification into hydrogen and biofuels, particularly in industrial applications.

#### Finland

In 2050 Finland’s total final energy demand is projected at roughly 220 TWh, distributed across the four main sectors of buildings, households, industry and transport. Electricity dominates the demand, accounting for the majority of the 18.34 TWh required by buildings (space‑heating, hot water and appliances) and the 42.4 TWh needed by households, where it supplies about 80 % of the sector’s consumption. In industry the electricity share is also substantial, with approximately 99.6 TWh (over 57 % of industrial demand) while hydrogen emerges as the second‑largest carrier at about 30.6 TWh, especially in chemicals (≈16.9 TWh) and steel (≈8.4 TWh); biofuels, heat and methane each contribute between 6 and 16 TWh. Transport consumes around 12.06 TWh, of which electricity provides roughly 10.8 TWh, liquids remain the largest single carrier at 10.2 TWh (driven by aviation and shipping), and hydrogen and methane add 1.3 TWh and 0.9 TWh respectively. Across all sectors the carrier mix reflects a strong electrification trend, with hydrogen playing a secondary role primarily in industry and modestly in transport, while liquids retain importance mainly for aviation and maritime applications.

#### France

The 2050 annual final energy demand for France shows electricity as the predominant carrier across all sectors. In the residential and building sector electricity accounts for roughly 118 TWh, powering appliances, space heating, hot water and cooling. The transport sector also relies heavily on electricity, with an estimated 106 TWh consumed by cars, vans, trucks and buses. Liquid fuels remain essential for international aviation and shipping, contributing about 50.7 TWh for aviation and 7 TWh for shipping, together approximately 63 TWh. Methane is used in buildings, households, industry and transport, with individual sector values ranging from 20 to 27 TWh, resulting in a modest overall share compared with electricity. Hydrogen appears in limited quantities, primarily in industry (chemicals, fertilizers) and in transport (trucks, trains, ships, planes), with a combined demand of roughly 4 to 5 TWh. Biofuels provide modest contributions, notably around 27 TWh in households and smaller amounts in other sectors. Heat, solids and other minor carriers together account for a very small fraction of the total demand. The overall profile indicates a clear shift toward electricity in domestic applications while retaining liquid hydrocarbons for long‑distance aviation and maritime transport and maintaining niche roles for methane, hydrogen and biofuels.

#### Germany

Germany's projected annual energy demand for 2050, as derived from the TYNDP 2024 demand figures using the energy transition model, highlights a significant transformation in energy carrier profiles across key sectors. This analysis focuses on the final energy demand for electricity, hydrogen, methane, and liquids, reflecting strategic adjustments made to align with future energy trends.   
  
Electricity emerges as the predominant energy carrier across all sectors in Germany. In the \*\*Buildings\*\* sector, which has a total projected consumption of 148.2 TWh, electricity primarily drives appliances, accounting for approximately 79 TWh, and supplies around 14.8 TWh for space heating and hot water, in addition to all cooling demands. Similarly, in \*\*Households\*\*, which exhibit a total demand of 297.81 TWh, electricity is crucial, accounting for approximately 98 TWh for appliances and around 85 TWh for combined space heating, hot water, and cooling. The \*\*Industry\*\* sector shows a substantial reliance on electricity, supplying approximately 392 TWh of its total energetic demand of 623.85 TWh. For the \*\*Transport\*\* sector, electricity is the largest carrier, projected at 152.1 TWh out of a total 269.4 TWh, powering key sub-sectors such as cars (83.9 TWh) and contributing to trucks (part of 56.3 TWh).  
  
Hydrogen plays a significant secondary role, particularly in the industrial and transport sectors. The \*\*Industry\*\* sector utilizes hydrogen for its energetic uses, contributing approximately 271 TWh to the sector's overall demand. Hydrogen is also involved in non-energetic uses, especially within chemicals. In the \*\*Transport\*\* sector, hydrogen is projected to account for 19.3 TWh, primarily in trucks and trains.  
  
Methane maintains a modest presence across various sectors. It is present in Buildings, Households, Industry, and Transport (notably for ships), with contributions noted to range from 1 to 28 TWh per sub-sector.  
  
Liquids primarily serve specific applications, mainly within the transport sector and for non-energetic industrial uses. In \*\*Transport\*\*, liquids are projected to constitute 91.1 TWh of the total demand, predominantly fueling international aviation (79.5 TWh). In \*\*Industry\*\*, liquids account for approximately 95 TWh of non-energetic uses, particularly within the chemicals sub-sector, contributing to the total non-energetic demand of 235.40 TWh.  
  
Direct thermal energy, or heat, also plays a crucial role for space heating and hot water requirements in both the Buildings and Households sectors, contributing roughly 15–68 TWh depending on the specific sub-sector. Biofuels are a minor energy carrier, recorded mainly in aviation with approximately 0.6 TWh, and in small quantities across Buildings, Households, and Industry.  
  
It is important to note that the provided dataset focuses exclusively on Germany's 2050 projections, thereby precluding direct cross-country comparisons or quantification of how Germany's reliance on these carriers may differ from other nations or from historical trends. To assess cross-country variations, similar sector-level carrier breakdowns for other European countries would be required.

#### Greece

In 2050 Greece’s projected annual final energy demand is distributed across the four main sectors with distinct carrier profiles. The transport sector dominates overall demand at roughly 59.6 TWh, of which electricity supplies 14.1 TWh, liquids 23.6 TWh and hydrogen contributes notably to heavy‑duty trucks (5.2 TWh) and shipping (1.4 TWh). The household sector is estimated at 25.9 TWh, driven primarily by electricity (appliances 6.3 TWh, cooling 1.8 TWh, space‑heating 3.2 TWh, hot‑water 2.2 TWh) with heat and bio‑fuels providing the remainder for space‑heating and hot‑water. Buildings account for about 12.0 TWh, where electricity is the clear leader at approximately 10.4 TWh, followed by methane at 0.8 TWh and minor contributions from heat, liquids and bio‑fuels. In industry, electricity again leads with around 15.5 TWh, while hydrogen emerges as the second‑largest carrier at about 9.2 TWh, reflecting both energetic and non‑energetic uses. Liquids account for roughly 5.6 TWh and methane for 2.6 TWh, with bio‑fuels, solid fuels and heat each exceeding 1 TWh. Across all sectors, electricity is the primary carrier, especially in buildings, households and most transport modes. Hydrogen is a significant secondary carrier in industry and heavy transport, whereas liquid fuels retain a strong presence in aviation (≈9.2 TWh) and maritime shipping (≈7.9 TWh). Methane, heat, and bio‑fuels play niche but sector‑specific roles, contributing modestly to the overall demand profile.

#### Hungary

Annual demand for Hungary in 2050 amounts to roughly 63 TWh across all sectors. The total is derived from sectoral figures: building sector 11.83 TWh, industrial sector electricity demand about 29 TWh, transport sector 22.87 TWh (of which electricity supplies 15.34 TWh). The household sector is not quantified in absolute terms but its composition is described in the ETM data. The final energy demand is split among four carriers: electricity, hydrogen, methane and liquids. Electricity dominates the overall demand, contributing the largest share in buildings (cooling and appliances), industry (≈45 % of industrial use) and transport (≈15.34 TWh, roughly 67 % of transport demand). Hydrogen appears primarily in industry, especially chemicals and fertilizers, representing about 19 % of industrial energy use. Methane is significant in households for space heating, in industry for steel and chemicals, and in transport for trucks, accounting for roughly 15 % of industrial demand and a notable share in residential heating. Liquids are the main carrier for aviation and buses and contribute about 11 % of industrial energy use. The sector‑specific breakdown highlights a diversified carrier mix: households rely on bio‑fuels (≈6.2 TWh) for space heating, buildings split heating between methane and electricity, industry combines electricity (≈45 % of its demand), hydrogen (≈19 %), methane (≈15 %) and liquids (≈11 %), while transport is electricity‑led (≈15.34 TWh) with liquids dominating aviation and buses and hydrogen supporting heavy‑duty trucks.

#### Ireland

The annual final energy demand for Ireland in the 2050 horizon is characterised by a clear hierarchy among the four principal carriers, electricity, methane, liquids and hydrogen, across the main end‑use sectors. In the building sector electricity dominates, accounting for roughly 76 % of the total building demand and delivering about 19.09 TWh. Methane contributes around 14 % of the building mix, while liquids, heat, bio‑fuels and solids each represent no more than 4 % of the sector’s demand. In households electricity remains the primary carrier, providing 7.98 TWh for appliances, 5.94 TWh for space‑heating and 4.37 TWh for hot‑water, together with smaller contributions from methane (≈1.8 TWh for heating and hot‑water) and heat. The industrial sector shows a more diversified carrier profile: electricity is still the largest share at approximately 32.9 TWh, driven largely by datacentres (21.4 TWh). Bio‑fuels follow with about 6.0 TWh, methane supplies roughly 3.9 TWh, hydrogen about 2.9 TWh and liquids around 3.1 TWh. Transport demand totals about 21.6 TWh, where electricity supplies the bulk for road and rail vehicles (≈7.5 TWh). Liquids dominate international aviation with about 9.1 TWh and constitute the largest single carrier in transport when all modes are aggregated (≈9.8 TWh). Hydrogen appears mainly in heavy‑duty trucks and ships, while methane is used across trucks, vans, buses and shipping (≈2.5 TWh). Across all sectors the final energy demand is heavily weighted toward electricity, which is the leading carrier in buildings, households, industry and road‑rail transport. Methane retains a niche but significant role in heating and heavy‑duty transport, liquids are confined largely to aviation and some shipping, and hydrogen and bio‑fuels remain relatively minor yet emerging contributors, particularly in industry and heavy transport. The presented figures reflect the TYNDP‑2024 demand outlook adjusted to align with the Terajoule view of future trends, and illustrate how Ireland’s carrier mix differs from other EU members based on its specific strategic pathways.

#### Italy

The 2050 annual energy demand for Italy amounts to roughly 667 TWh when summed across the four major sectors: 176 TWh for households, 105 TWh for buildings, 236 TWh for industry and 150 TWh for transport. When the demand is expressed by final energy carrier, the distribution highlights a dominant role for electricity, followed by methane, liquids and hydrogen. Electricity accounts for about 428.7 TWh, comprising the entire household demand (≈176 TWh), the bulk of building demand (≈66 TWh), the largest share of industry (≈90 TWh) and the majority of transport (≈96.7 TWh, driven by electric cars, vans and trucks). Hydrogen appears mainly in industry (≈17 TWh) and heavy‑duty transport (≈12.5 TWh), totaling roughly 29.5 TWh. Methane is still significant in buildings (≈35 TWh), industry (≈20 TWh) and transport (≈27 TWh), giving an aggregate of about 82 TWh; household methane use is not quantified in the available data. Liquids, largely associated with aviation and maritime transport, represent about 49.3 TWh. Summing the reported carrier figures yields an estimated 589.5 TWh of final energy demand, indicating that a portion of sectoral totals is allocated to carriers not explicitly detailed in the dataset (e.g., biofuels, district heat, solid fuels). The pattern underscores a strong shift toward electricity across all sectors, while methane retains importance in heating and transport, and hydrogen emerges as a growing contributor in industry and heavy transport. Liquids remain essential for aviation and shipping, preserving a non‑negligible share of total demand.

#### Latvia

The 2050 annual energy demand for Latvia (LV) is shaped by various final energy carriers across key sectors, as projected by the TYNDP 2024 demand figures utilizing the Energy Transition Model (ETM). These figures reflect a distributed energy scenario, with adjustments made to align with future trends. The final energy demand considers specific carriers such as hydrogen, electricity, methane, and liquids, alongside significant contributions from heat and biofuels. A direct comparison with 2019 data or other countries is not possible due to the scope of the provided dataset, thus the analysis focuses solely on Latvia's projected 2050 energy landscape.  
  
In 2050, Latvia's total energy demand from the ETM database highlights the Industrial sector as the largest consumer, estimated at approximately 6.91 TWh. This is closely followed by the Households sector at around 5.90 TWh and the Transport sector at approximately 5.88 TWh. The Buildings sector shows a demand of about 3.05 TWh.  
  
A breakdown of energy carriers within each sector reveals distinct consumption patterns:  
  
\* \*\*Households:\*\* The sector's demand of 5.90 TWh is primarily driven by space heating and hot water needs. Heat emerges as the dominant carrier, accounting for 2.59 TWh for space heating and 0.63 TWh for hot water. Electricity also plays a significant role, contributing 0.98 TWh for heating and 0.35 TWh for hot water. Methane supplies a more modest share, with 0.40 TWh for heating and 0.14 TWh for hot water. Cooling demand in this sector is negligible.  
\* \*\*Buildings:\*\* With an anticipated consumption of 3.05 TWh, the Buildings sector sees electricity as the leading carrier for appliance use, demanding 1.501 TWh. Heat is substantial for space heating and hot water, at 0.588 TWh. Methane and biofuels contribute to heating, albeit in secondary roles.  
\* \*\*Industry:\*\* The Industrial sector is projected to have the highest overall demand, approximately 6.91 TWh in 2050. Energetic uses, totaling around 6.43 TWh, are largely attributed to the 'Others' subsector. Biofuels provide a significant contribution of 3.15 TWh within this subsector. Electricity is another primary carrier, with 1.27 TWh consumed within the 'Others' subsector and an additional 0.646 TWh for datacenters. Methane, hydrogen, heat, and solids each contribute less than 0.1 TWh, indicating minor roles in the overall industrial energy mix.  
\* \*\*Transport:\*\* This sector's demand of 5.88 TWh shows a diversified carrier mix. Electricity is a major carrier for passenger transport, accounting for 1.74 TWh in cars, 0.22 TWh in vans, 0.08 TWh in passenger trains, and 0.35 TWh in freight trains. Liquid fuels remain crucial for international aviation (1.28 TWh) and shipping (0.93 TWh). Hydrogen appears as an emerging carrier, with 0.27 TWh used in trucks and a total of 0.07 TWh in rail transport. Methane is present in shipping and trucks but at lower consumption levels.  
  
Overall, Latvia's 2050 energy system demonstrates a strong reliance on heat for residential heating and hot water, while electricity is projected to be a primary energy carrier across both the industrial and transport sectors, particularly for appliances and road/rail transport. Liquid fuels maintain their importance for international aviation and shipping. Biofuels play a considerable role in industrial energetic uses, and hydrogen is noted for its emerging, albeit smaller, contribution to specific transport segments. The absence of comparable 2019 data or data from other European countries precludes any cross-country comparative analysis or assessment of historical trends, limiting the scope of this report to Latvia's internal projected 2050 energy carrier landscape.

#### Lithuania

Lithuania's projected energy demand for 2050, as derived from the TYNDP 2024 demand figures and the energy transition model, illustrates a future energy landscape shaped by a distributed energy scenario with specific adjustments aligning with future trends. The analysis focuses on the final energy demand for key carriers: hydrogen, electricity, methane, and liquids, providing a comprehensive breakdown across major sectors.  
  
The industrial sector is anticipated to be the largest consumer of energy in Lithuania by 2050, with a total projected demand of approximately 27.68 TWh. This demand is split between 11.76 TWh for energetic uses, primarily driven by electricity and hydrogen, and a substantial 15.92 TWh for non-energetic purposes, predominantly hydrogen utilised in fertilizer and chemical production. Overall, hydrogen is expected to dominate the industrial sector's carrier reliance, accounting for approximately 15 TWh, followed by electricity at around 6.5 TWh and liquids at approximately 3.8 TWh. Biofuels and methane are projected to play minor roles within this sector.  
  
In the transport sector, the energetic demand is estimated at around 8.24 TWh. Cars are identified as the largest subsector consumer, demanding 3.76 TWh, largely met by electricity. Trucks, international aviation, and shipping contribute to the remaining demand. For carrier reliance, electricity stands out as the largest carrier, at approximately 4.3 TWh, with liquids as the second most significant at around 2.2 TWh. Hydrogen holds a smaller share, approximately 0.8 TWh, while methane accounts for the least.  
  
Households are projected to demand 7.76 TWh. Space heating represents the leading component of this demand, at 4.69 TWh, primarily met by a combination of heat, electricity, and methane. Significant consumption is also attributed to appliance use and hot water. Similarly, the building sector's demand for space heating and hot water is met by heat, electricity, and methane. Appliance use within buildings is largely dependent on electricity, consuming an estimated 2.236 TWh.  
  
Across the residential (Households) and building sectors, electricity emerges as the primary energy carrier for space heating, hot water, and appliances. Heat provides the largest share specifically for space heating and hot water in buildings, while methane contributes modestly across these end-use sectors. A clear shift in carrier reliance is observed across the economy, moving from electricity in end-use sectors such as households and transport to a significant reliance on hydrogen in heavy industry. The provided data for Lithuania for 2050 does not include 2019 comparative figures, nor does it allow for direct cross-country comparisons of energy carrier reliance.

#### Luxembourg

Luxembourg's annual energy demand for 2050, as projected by the TYNDP 2024 demand figures using an energy transition model, reveals a system heavily reliant on electrification across all major sectors. These projections are based on a distributed energy scenario, with adjustments to align with future trends in coordination with European TSOs. Final energy demands are considered for key carriers: hydrogen, electricity, methane, and liquids, with other carriers playing comparatively marginal roles.  
  
The Transport sector is projected to be the largest consumer, accounting for approximately 20.25 TWh. Within this sector, international aviation is a significant driver, demanding 12.26 TWh of liquid fuels. Domestic transport modes, however, show a strong orientation towards electricity; cars are projected to consume 2.64 TWh, trucks 2.75 TWh, buses 0.43 TWh, passenger trains 0.47 TWh, and freight trains 0.06 TWh, all primarily supplied by electricity. Hydrogen also emerges as an energy carrier for trucks (1.08 TWh) and, to a very minor extent, ships (approximately 0.00016 TWh).  
  
In the Industrial sector, the total demand is estimated at around 6.09 TWh. Steel production is the dominant subsector, contributing 3.81 TWh to this total. Electricity is the primary energy carrier for industry, projected at approximately 3.52 TWh, followed by methane at about 1.70 TWh. Hydrogen also contributes meaningfully, with an estimated demand of 0.58 TWh. Other carriers like biofuels, solids, heat, and liquids each contribute less than 0.1 TWh.  
  
The Buildings sector is expected to consume approximately 3.31 TWh. Within this, electricity accounts for about 1.47 TWh for appliances and 0.46 TWh for space heating and hot water. Methane and heat together supply just over 0.6 TWh for heating and hot water needs.  
  
For Households, the total demand is estimated at about 2.83 TWh. Electricity is the leading energy source, supplying roughly 1.65 TWh, which constitutes approximately 55% of the total household demand. Methane serves as the secondary carrier, accounting for about 0.73 TWh, with only minor contributions from heat and biofuels.  
  
Across all sectors, electricity stands out as the most prominent energy carrier for Luxembourg in 2050, underpinning domestic transport, industrial processes, and a majority of energy needs in both buildings and households. Methane serves as the principal backup, especially in heating applications and for industrial energy requirements. Liquids remain crucial for international aviation, while hydrogen demonstrates a limited but growing presence in heavy-duty transport and industry. The current dataset, however, provides only 2050 figures for Luxembourg and lacks comparable 2019 baseline data or information for other countries, thereby preventing any direct year-on-year trend analysis or cross-country comparisons of energy demand evolution.

#### Malta

The following chapter outlines Malta's (MT) projected final energy demand for 2050, focusing on key energy carriers: hydrogen, electricity, methane, and liquids. These demand figures are derived from the TYNDP 2024 report, which utilizes a comprehensive energy transition model. The data has been developed in coordination with Transmission System Operators (TSOs) across European Union countries. While the initial scenario premises a distributed energy approach, certain adjustments have been incorporated to align with Terajoule’s views on future energy trends. A detailed breakdown is provided for Malta, noting the absence of 2019 baseline data, which precludes year-on-year comparisons, and the lack of comparable data for other countries limits cross-country analysis.  
  
In 2050, Malta's energy demand profile exhibits distinct patterns across various sectors. The household sector demonstrates a significant reliance on electricity, with approximately 1.084 TWh allocated across its main end-uses. Specifically, electricity is the primary source for space heating (0.168 TWh), cooling (0.135 TWh), hot water (0.373 TWh), and appliances (0.408 TWh). Methane contributes a comparatively small 0.070 TWh to appliance demand, while biofuels account for a marginal 0.001 TWh in the same category.  
  
Similarly, within the building sector, final energy demand, totaling approximately 0.74 TWh, is predominantly met by electricity, which supplies over 98% of the sector's needs. This encompasses 0.2996 TWh for heating and hot water, 0.0864 TWh for cooling, and 0.3539 TWh for appliances. Methane and liquids represent minor contributions to appliance demand, registering 0.0054 TWh and 0.0022 TWh, respectively.  
  
The industrial sector in Malta primarily depends on electricity for its energy requirements, consuming around 0.34 TWh across various sub-sectors, including chemicals, food, paper, and datacenters. Other energy carriers play more limited roles in this sector: hydrogen demand is 0.0412 TWh, biofuels account for 0.0137 TWh, and methane contributes 0.0027 TWh.  
  
The transport sector constitutes the largest share of Malta's overall final energy demand, estimated at approximately 12.6 TWh by 2050, and showcases a markedly different carrier mix. Liquids are the dominant energy carrier, comprising about 8.79 TWh, which represents roughly 70% of the total transport energy. Methane follows with approximately 2.40 TWh, while electricity provides about 1.22 TWh, and hydrogen contributes a smaller share of approximately 0.13 TWh. A more granular view reveals that international aviation alone demands 1.345 TWh of liquids, and international shipping accounts for a substantial 9.526 TWh, predominantly supplied by methane and liquids. Domestically, electric power is a key energy source for vans (0.830 TWh) and buses (0.018 TWh), while trucks (0.294 TWh total demand) utilize hydrogen alongside electricity. Other road vehicles contribute 0.118 TWh to demand, and ships account for 0.102 TWh.

#### Netherlands

The 2050 annual energy demand for the Netherlands is dominated by electricity across all sectors, with heat remaining a significant carrier for thermal services and hydrogen emerging as a sizable contributor in industry and transport. In the residential sector, final electricity demand reaches roughly 19 TWh, primarily for appliances and cooling, while space‑heating is split between heat (about 18 TWh) and electricity (about 12 TWh). The broader building sector adds another 19.3 TWh of electricity for appliances, 3.7 TWh for cooling and about 12 TWh of heat for space‑heating and hot‑water, bringing total building‑related electricity to roughly 35 TWh. Industry shows the strongest shift toward electricity, with an estimated 55‑70 TWh (midpoint ≈ 62.5 TWh) of final demand, while hydrogen contributes between 9 and 68 TWh (midpoint ≈ 38.5 TWh), especially in refineries and chemical production. Transport is increasingly electrified; domestic road transport accounts for about 38 % of total transport energy, although absolute values are not disclosed. Hydrogen appears mainly in heavy‑duty trucks (≈ 8 TWh). International shipping and aviation continue to rely on fossil carriers: methane supplies roughly 39 TWh, liquid fuels about 25 TWh, and bio‑fuels around 23 TWh for aviation. Summarising the carrier mix, electricity accounts for the largest share of final demand (≈ 119 TWh when aggregating residential, building, and industrial uses), heat contributes about 30 TWh, hydrogen roughly 46 TWh, methane 39 TWh, liquids 25 TWh, and bio‑fuels 23 TWh. These figures illustrate the Netherlands’ transition toward an electricity‑centric energy system, with hydrogen gaining relevance in industry and transport, while fossil carriers remain confined to specific international mobility sectors.

#### Poland

Poland’s projected final energy demand for 2050 amounts to roughly 400 terawatt‑hours (TWh) when all sectors are summed. The industrial sector dominates the total with an estimated 218.2 TWh, of which 154.9 TWh is energetic use and 63.2 TWh is non‑energetic. Electricity is the leading carrier in industry, accounting for about 94.9 TWh. The transport sector follows with 94.8 TWh, driven primarily by electricity (57.0 TWh) and supported by liquids for cars, trucks, aviation and shipping, although the exact liquid quantity is not specified. Households contribute roughly 66 TWh, split between electricity (approximately 33 TWh) and heat (about 32.8 TWh) for space heating and hot‑water supply. The building sector adds another 29.4 TWh of electricity demand, largely for appliances and space‑heating, with additional heat demand not detailed. Hydrogen emerges as a significant industrial carrier, with 39.6 TWh used for non‑energetic purposes such as chemicals and fertilizers and for energetic processes like steel production. Methane provides a modest but consistent contribution across industry, households and buildings, though precise values are not disclosed. Liquids retain a sector‑specific niche, remaining essential for transport despite an overall shift toward electricity. In summary, electricity accounts for roughly 214 TWh (about 53 % of the total demand), hydrogen contributes close to 40 TWh (10 %), heat supplies around 33 TWh (8 %), while the remaining demand is covered by methane and liquids, reflecting Poland’s transition toward an electricity‑heavy energy mix with growing industrial hydrogen use.

#### Portugal

Portugal’s 2050 annual final energy demand is characterised by a strong dominance of electricity across all major sectors, with hydrogen emerging as a secondary carrier in industry and transport and liquid fuels retained for aviation and shipping. The total annual demand across households, buildings, industry and transport amounts to roughly 98‑99 TWh. Electricity accounts for approximately 57 TWh, representing about 58 % of the total demand. In the residential and building sectors, electricity provides 8.0 TWh for space heating, hot water, appliances and cooling in households and about 8.6 TWh in the broader building stock, while methane (≈3 TWh), bio‑fuels (≈1.6 TWh) and direct heat (≈1.7 TWh) play minor roles. The industrial sector, the largest consumer, requires about 49.8 TWh, of which roughly 22 TWh is electricity and 13 TWh is hydrogen, reflecting the sector’s diversification and the growing role of hydrogen for both energetic and non‑energetic applications. Liquid fuels, bio‑fuels and methane each remain below 6 TWh in industry. Transport consumes about 37.6 TWh; electricity supplies roughly 18.5 TWh (cars, trucks, vans, trains and a share of aviation), liquids dominate long‑haul aviation and shipping with about 15.8 TWh (≈11.9 TWh for international aviation and ≈3.1 TWh for shipping), and hydrogen contributes a secondary share, particularly for heavy‑duty trucks, ships and emerging aviation applications. Methane and bio‑fuels in transport are marginal. The carrier‑specific breakdown therefore highlights electricity as the primary energy carrier (≈57 TWh), followed by hydrogen (≈13–14 TWh), liquids (≈16 TWh) and methane (≈3 TWh). This pattern aligns with the TYNDP 2024 demand figures and the European energy transition model, which projects a continued shift toward electrification while retaining hydrogen and liquid fuels where direct electrification is less feasible.

#### Romania

The 2050 projection for Romania shows a total final energy demand of approximately 154.8 TWh. The demand is distributed across four primary carriers – electricity, hydrogen, methane and liquid fuels – with smaller contributions from bio‑fuels, heat and solids. In the industrial sector, electricity dominates with about 31.8 TWh, driven mainly by the “Others”, chemicals and datacenter subsectors, while hydrogen accounts for roughly 22.6 TWh, largely used in “Others” and fertilizer production. Methane supplies about 7.7 TWh, concentrated in steel, and liquids provide around 5.4 TWh for non‑energetic uses. Households consume close to 47.8 TWh, of which space‑heating relies heavily on bio‑fuels (10.7 TWh) and heat (6.8 TWh), complemented by electricity (5.9 TWh) and methane (4.7 TWh). Cooling is almost entirely electric (0.3 TWh), while hot‑water provision mixes bio‑fuels (3.2 TWh), electricity (2.5 TWh), heat (2.0 TWh) and methane (1.9 TWh). Appliances in homes are powered by electricity (3.6 TWh) and methane (3.7 TWh) with a smaller share of bio‑fuels (2.4 TWh). The building sector adds roughly 10.6 TWh, where heat (0.98 TWh) and electricity (0.71 TWh) are the main carriers for space heating and hot water, and methane contributes 0.69 TWh. Transport demands 23.7 TWh, of which electricity supplies about 72 % (≈17.2 TWh), liquids about 16.5 % (≈3.9 TWh), hydrogen 8 % (≈1.9 TWh) and methane 2.8 % (≈0.7 TWh). Overall, the analysis highlights a pronounced shift toward electrification across residential, building and transport sectors, while hydrogen emerges as a significant industrial fuel and a growing component of heavy‑duty transport. Methane retains a notable presence in heating, appliances and specific industrial processes, and bio‑fuels remain important for residential heating and hot‑water supply.

#### Slovakia

Slovakia's projected energy demand for 2050, as outlined by the TYNDP 2024 demand figures and an energy transition model, indicates a landscape significantly shaped by electrification and the emergence of new energy carriers. These figures, developed in coordination with European TSOs, incorporate adjustments to align with anticipated future trends. The analysis considers final energy demand across key carriers including electricity, hydrogen, methane, and liquids, alongside other contributions such as direct heat and biofuels.  
  
In the industrial sector, the total energy demand is projected to be approximately 46.4 TWh, comprising 33.8 TWh for energetic uses and 12.6 TWh for non-energetic applications. Electricity emerges as the primary carrier, accounting for roughly 17.45 TWh. Hydrogen plays a significant dual role, contributing approximately 6.6 TWh for energetic purposes and 8.8 TWh for non-energetic applications, totaling around 15.34 TWh, reflecting its increasing importance in industrial processes. Methane remains a substantial contributor, particularly for applications like steel production, with a demand of around 6.65 TWh. Liquids contribute 3.38 TWh, while biofuels (2.57 TWh), solids (0.74 TWh), and heat (0.23 TWh) complete the energy mix.  
  
Households are projected to consume around 15 TWh, with primary demands for space heating and hot water. Electricity is a dominant carrier in this sector, used for space heating (approximately 2.85 TWh), cooling (0.025 TWh), hot water (1.50 TWh), and appliances (2.00 TWh). Methane remains a significant energy source, especially for space heating (2.46 TWh) and hot water (1.21 TWh). Direct heat (district heating) provides a comparable share for space heating at 2.98 TWh, while biofuels contribute marginally, less than 0.1 TWh.  
  
The broader building sector demonstrates a considerable reliance on electricity, which accounts for roughly two-thirds of its total use, approximately 4.40 TWh out of 6.64 TWh. Methane is the second most important carrier in this sector, mainly for space heating and appliances, with a demand of around 1.29 TWh. Direct heat contributes 0.63 TWh, with biofuels, solid fuels, and liquids each contributing less than 0.1 TWh.  
  
For the transport sector, total consumption is also around 15 TWh. Electrification is a key trend, with electricity leading at approximately 9.75 TWh, driven by its adoption in cars, vans, and trucks. Liquids represent the second-largest share, approximately 2.50 TWh, primarily utilized in trucks, vans, and aviation, highlighting their continued necessity for high-energy-density applications. Methane and hydrogen also contribute to the transport energy mix, though at smaller scales, with approximately 1.51 TWh and 1.29 TWh respectively.  
  
Overall, electricity emerges as the dominant energy carrier across all sectors, particularly in households, buildings, and transport, signaling a broad trend towards electrification. Methane retains a strong role in heating applications within households and buildings, and in heavy industry processes. Hydrogen is poised to become a major carrier in the industrial sector, reflecting a strategic shift towards low-carbon process fuels. Liquids remain essential for specific segments of the transport sector, while biofuels, solid fuels, and direct heat contribute smaller but notable shares across various sectors.

#### Slovenia

Slovenia's (SI) projected annual energy demand for 2050, derived from TYNDP 2024 demand figures and modelled using an energy transition model, illustrates a significant shift in energy carrier profiles. These projections, developed in coordination with European TSOs and stemming from a distributed energy scenario with subsequent adjustments, detail final energy demand across key sectors. The overall energy landscape points towards a stronger reliance on electricity, hydrogen, methane, and liquids, with specific nuances for each sector.  
  
Total energy demand in 2050 for Slovenia is estimated at approximately 7.84 TWh for the household sector, 2.83 TWh for the building sector, 10.39 TWh for industry, and 7.82 TWh for transport.  
  
In the \*\*household sector\*\*, space heating is projected to be met primarily by district heat (1.300 TWh) and biofuels (1.245 TWh), with methane contributing 0.699 TWh and electricity 0.532 TWh. Cooling demand is almost entirely electric, requiring 0.128 TWh. Hot water provision is diversified, with heat accounting for 0.849 TWh, biofuels 0.723 TWh, methane 0.536 TWh, and electricity 0.415 TWh. Appliance use is predominantly electric, consuming 1.025 TWh, complemented by methane at 0.468 TWh.  
  
The \*\*building sector\*\* shows electricity as the dominant carrier for appliances, demanding 1.919 TWh. For space heating and hot water in buildings, heat (as a carrier) represents the largest share at 0.263 TWh, followed by electricity at 0.174 TWh, while methane and liquids play minor roles.  
  
\*\*Industry\*\* displays a more varied energy mix. Electricity is the primary carrier across industrial sub-sectors, accounting for approximately 5 TWh. Hydrogen plays a notable role, contributing around 0.9 TWh. Methane provides approximately 1.38 TWh, and biofuels and solids collectively add another 0.9 TWh. Liquids and heat contribute less than 0.2 TWh each.  
  
The \*\*transport sector\*\* is projected to undergo substantial electrification, with electricity supplying about 61.5% of total transport energy, equivalent to approximately 4.8 TWh, mainly driven by cars, trucks, and buses. Liquids account for about 18.3% (approximately 1.4 TWh), primarily utilized in international shipping and aviation. Methane contributes around 11.2% (approximately 0.9 TWh), and hydrogen accounts for about 8.9% (approximately 0.7 TWh).  
  
Overall, Slovenia's 2050 energy mix is characterized by a strong shift towards electricity and bio-based heat in the residential and building sectors. Industry maintains a more diversified mix, with a significant hydrogen component alongside electricity and methane. Transport emerges as the most electrified sector, reflecting a broader decarbonisation trend.  
  
It is important to note the limitations of this analysis: only 2050 demand figures for Slovenia are available, precluding any year-over-year trend quantification or direct comparison of carrier reliance across different European countries. A robust cross-country assessment would necessitate comparable datasets for other nations, ideally including baseline figures such as 2019 data.

#### Spain

The 2050 annual energy demand for Spain (ES) is characterised by a dominant reliance on electricity across all major sectors, with hydrogen, methane and liquids contributing smaller but sector‑specific shares. Buildings account for roughly 60.5 TWh of final energy demand; electricity supplies about 83 % of this (≈50.3 TWh), while liquids and methane together represent the remaining 17 % (≈2.5 TWh liquids and ≈7.7 TWh methane). Heat and biofuels are marginal in this sector. Household demand totals approximately 78.3 TWh, almost entirely met by electricity (space heating, cooling, hot‑water and appliances). Heat (0.91 TWh) and biofuels (0.06 TWh) are negligible. Industry consumes around 217.7 TWh, with electricity providing the largest portion (≈84.2 TWh). Hydrogen is a significant secondary carrier (≈72.7 TWh), especially in chemicals and the “others” subsector, while methane accounts for about 17.0 TWh, primarily in steel, refineries and metals. Biofuels appear mainly in the chemical sector (≈36.9 TWh, largely non‑energetic). Transport demand reaches 196.3 TWh. Electricity dominates this sector as well (≈123.4 TWh), covering cars, buses, trucks, vans, rail and most maritime traffic. Liquids retain a sizable share (≈52.9 TWh), largely for heavy‑duty trucks and aviation. Hydrogen contributes around 18.5 TWh, mainly in shipping and some aviation applications, while methane is minor (≈1.5 TWh). Overall, the final energy demand composition for Spain in 2050 shows electricity exceeding 80 % of total demand in buildings, households and transport, hydrogen emerging as a niche carrier in industry and maritime transport, and fossil‑based liquids and methane persisting in transport and specific industrial processes. The dataset provides only projected 2050 figures, limiting year‑on‑year trend analysis, but the distribution across carriers highlights a pronounced shift toward electrification and early‑stage hydrogen uptake.

#### Sweden

In 2050 Sweden’s final energy demand reaches roughly 331 TWh, distributed across the main sectors and energy carriers. The industrial sector dominates with an estimated 226 TWh, of which about 139 TWh is supplied by electricity, 48 TWh by hydrogen and 30 TWh by biofuels, while methane contributes roughly 5.5 TWh. The transport sector accounts for 41.6 TWh, driven primarily by electricity (≈21.6 TWh) and liquid fuels (≈13.5 TWh); methane supplies around 3.9 TWh and hydrogen about 0.7 TWh, reflecting early niche applications in shipping and rail. The building sector’s demand is about 23.7 TWh, with electricity providing the bulk (≈13 TWh for appliances and 3.8 TWh for heating and cooling) and district heat (heat carrier) delivering roughly 5.1 TWh for space‑heating. Households, embedded within the building category, exhibit a strong electrification pattern: electricity covers space‑heating (≈11.6 TWh), hot‑water (≈9.9 TWh) and appliances (≈9.9 TWh), while district heat contributes about 15.6 TWh for space heating. Hydrogen’s presence is modest outside industry, limited to around 0.7 TWh in transport, indicating its role in sectors where direct electrification is challenging. Liquids remain essential for long‑distance mobility, supplying 13.5 TWh mainly to international aviation and shipping, whereas methane’s share is confined to specific industrial processes and a small portion of transport. Overall, the data illustrate a pronounced shift toward electricity across all sectors, sustained importance of district heat in residential heating, and emerging but still limited use of hydrogen and liquids for hard‑to‑electrify applications.

#### United Kingdom

In 2050, the United Kingdom's final energy demand is projected to be approximately 893.38 TWh across the household, building, industrial, and transport sectors. This demand is met by a diversified energy mix, primarily comprising electricity, hydrogen, methane, and liquids, alongside contributions from heat and biofuels. The distribution and reliance on these carriers vary significantly by sector, reflecting specific end-use requirements and strategic energy transitions.  
  
The household sector's total energy consumption in 2050 is projected at approximately 208.65 TWh. Space heating constitutes the largest share at about 111.14 TWh, with electricity supplying 48.34 TWh, methane 15.54 TWh, direct heat 41.35 TWh, and biofuels 5.90 TWh. Hot-water demand accounts for roughly 53.21 TWh, distributed among electricity (26.82 TWh), methane (8.82 TWh), heat (15.35 TWh), and biofuels (2.22 TWh). Appliances consume approximately 43.68 TWh, primarily from electricity (32.89 TWh), with methane contributing 10.76 TWh and biofuels a negligible 0.03 TWh. Cooling demand is minimal, met entirely by electricity at 0.62 TWh.  
  
For the building sector, energy demand totals approximately 141.17 TWh. Space heating and hot water collectively demand 20.09 TWh, composed of 8.53 TWh electricity, 2.66 TWh methane, 8.70 TWh heat, and 0.20 TWh biofuels. Cooling relies on 2.20 TWh of electricity. Appliances are the dominant consumer in this sector, requiring 118.88 TWh, largely from electricity (86.74 TWh), followed by methane (29.07 TWh), liquids (3.03 TWh), and biofuels (0.04 TWh).  
  
The industrial sector is projected to have a total energy demand of 268.46 TWh in 2050, split between 193.30 TWh for energetic uses and 75.16 TWh for non-energetic applications. The largest subsectors are ‘Others’ at 109.62 TWh and Chemicals at 78.92 TWh. Across all industrial uses, electricity (104.91 TWh), hydrogen (73.26 TWh), and liquids (35.38 TWh) are the dominant carriers. Specifically for energetic applications, electricity (104.28 TWh), hydrogen (38.01 TWh), and methane (24.82 TWh) are primary. For non-energetic uses, hydrogen (37.39 TWh) and liquids (31.23 TWh) are the most significant.  
  
Finally, the transport sector's total energy demand in 2050 is estimated at 275.1 TWh. International aviation is a major contributor, requiring 98.7 TWh, predominantly from liquids. Domestic cars demand 76.5 TWh, with electricity accounting for a substantial 69.4 TWh. Trucks require 46.6 TWh, supplied by a mix of liquids (16.5 TWh), hydrogen (11.2 TWh), electricity (9.9 TWh), and methane (8.8 TWh). Sector-wide, liquids are the most dominant carrier at 128.7 TWh, followed by electricity (108.4 TWh), methane (21.5 TWh), and hydrogen (16.5 TWh).  
  
In summary, electricity emerges as a dominant energy carrier across virtually all sectors, particularly for household space heating, appliances, building heating, industrial processes, and most domestic transport modes. Hydrogen plays a significant and growing role, especially in industry and heavy-duty transport. Methane maintains a notable, albeit secondary, presence in household hot water, appliances, and certain transport segments. Liquids remain critical for long-distance aviation and heavy freight, highlighting their persistence in sectors demanding high energy density. Biofuels and direct heat contribute smaller but consistent shares across various applications.

## 3.3 Industrial Profiles

Industrial Profiles – EU Annual Demand  
The European Union’s industrial sector exhibits distinct demand patterns across its major subsectors. Steel production, chemical manufacturing, paper, cement, ceramic, and glass industries maintain relatively constant annual consumption levels, reflecting steady domestic and export markets. For example, EU steel output averages around 140 million tonnes per year, with monthly variations typically within ±5 percent, indicating a flat demand curve. Chemical production, valued at approximately €250 billion annually, shows a similar stability, with demand fluctuations driven mainly by minor seasonal shifts in downstream sectors such as automotive and construction.  
In contrast, the agricultural sector displays pronounced seasonal demand. Fertilizer and agro‑chemical consumption peaks during planting months (April–June) and again during harvest support (September–October), creating a bi‑modal demand profile. EU fertilizer use reaches roughly 12 million tonnes per year, with monthly demand ranging from 0.8 million tonnes in winter to 1.5 million tonnes in spring.  
Paper production, while largely flat, experiences slight upticks in the fourth quarter due to increased packaging demand during holiday retail cycles, raising output from an average of 60 million tonnes to about 62 million tonnes. Cement production, at roughly 350 million tonnes annually, shows modest seasonal variation linked to construction activity, with a 3‑4 percent increase in summer months.  
Ceramic and glass manufacturers also follow stable annual trajectories. EU glass production stands at about 120 million tonnes per year, with demand remaining within a ±4 percent band throughout the year. Ceramic output, valued near €15 billion, similarly experiences limited seasonal swings, primarily tied to the building sector’s construction calendar.  
Overall, the EU’s industrial demand profile is characterized by a baseline of flat consumption across most heavy industries, overlaid by sector‑specific seasonal peaks in agriculture, construction‑linked materials, and packaging‑driven paper demand. These patterns are essential for capacity planning, inventory management, and forecasting within the EU’s diversified industrial landscape.

### 3.3.2 Seasonal Industrial Profiles

Chapter 3.3.2 – Industrial Profiles, Seasonal Industrial Profiles  
  
The seasonal industrial demand profile for the European Union exhibits pronounced variations throughout the year, driven primarily by temperature‑dependent processes, production cycles, and energy‑intensive activities such as metalworking, chemicals, and food processing. Annual demand curves reveal higher consumption during winter months (December–February) and summer months (June–August), with a relative trough in spring (April–May) and autumn (September–October).   
  
In the winter period, heating requirements for process plants and increased electricity use for auxiliary systems raise the industrial load by roughly 8‑12 % above the annual average. Conversely, the summer peak is associated with cooling loads, intensified refinery operations, and heightened activity in the agro‑industrial sector, contributing an additional 6‑10 % above the average. The combined effect of these two peaks results in a bimodal seasonal pattern that must be accommodated by the power system’s flexibility resources.   
  
When aggregating the seasonal profiles across all nodes and energy carriers (electricity, natural gas, district heat, and steam), the overall industrial demand curve retains the dual‑peak shape. The magnitude of the seasonal swing translates into a net annual demand of approximately X TWh (electricity) and Y PJ (thermal), with the winter peak contributing Z TWh and the summer peak contributing W TWh. These peaks impose specific requirements on peaking capacity: the system must be capable of delivering an additional 5‑7 % of total industrial capacity during the identified high‑demand windows to avoid supply deficits.   
  
The seasonal variability also influences the temporal distribution of fuel consumption. Natural gas usage rises by about 10 % in winter, while electricity consumption for cooling rises by roughly 8 % in summer. This shift affects the load profile of the gas network and the electricity grid, respectively, and highlights the need for coordinated operation of cross‑carrier storage and conversion assets.   
  
In summary, the EU’s seasonal industrial demand profile is characterized by two distinct peaks that together shape the overall industrial load. These peaks must be explicitly modeled to ensure that sufficient peaking capacity and flexible resources are available, thereby maintaining system reliability throughout the year.

## 3.4 Transport Profiles

### 3.4.1 Cars

The annual demand for passenger cars across the European Union is undergoing a profound transformation, primarily driven by the widespread adoption of electric vehicles (EVs). By 2050, the aggregated electricity consumption for cars within the EU is projected to be approximately 503 TWh, signaling a significant shift away from traditional liquid fuels. This substantial demand is not uniformly distributed but is instead derived from a granular modelling approach that captures the diverse usage patterns of different population segments and vehicle types. Notable contributions to this electricity demand come from countries such as Germany (83.87 TWh), the United Kingdom (69.41 TWh), Spain (62.5 TWh), Italy (60.63 TWh), and France (46.79 TWh), reflecting the scale of their respective transport sector electrification.  
  
The overall annual car demand is built upon detailed daily driving profiles, which are segmented by age groups and their associated car ownership rates. Population data for each node is drawn from EUROSTAT, categorised into Child (2-15), Teen (16-24), Adult (25-64), and Senior (65+) cohorts. Each of these age groups is assigned a percentage of its population that owns cars, forming the baseline for vehicle fleet size. To understand daily usage, a comprehensive set of activities is considered, including School Run, Evening Activities, Daily Activities, Part Time Workers, Remote Workers, Evening Leisure, and Night Life. These activities are weighted according to the day of the week, reflecting variations such as school schedules or weekend leisure patterns. For instance, a child's driving profile would incorporate activities like school runs and daily excursions, with varying weights across weekdays and weekends. Consequently, each geographical node develops its unique driving profiles, influenced by its specific population demographics, age structure, and typical daily activities.  
  
Further refinement of the car fleet demand involves segmenting vehicles by the employment status of their primary users: Full-time workers, Part-time workers, and Remote workers. Crucially, these groups are also differentiated by their primary charging infrastructure: Home Charging or Street Charging. Vehicles connected to home chargers contribute to the demand profile of residential nodes, often leading to pronounced evening peaks as drivers return home and plug in. Conversely, vehicle fleets relying on street chargers exhibit a more dispersed demand pattern, leveraging 24/7 availability with a notable concentration of charging activity at tertiary nodes between 09:00 and 20:00. This spatial and temporal distribution of charging significantly shapes the daily load curves, with many countries observing distinct morning and evening electricity demand peaks associated with commuting and post-work charging, along with a midday dip when vehicles are typically in use or parked.  
  
Seasonal factors also introduce variations in annual car demand. In colder months, increased energy is required for EV battery pre-conditioning and cabin heating, contributing to higher electricity consumption, often overlapping with increased residential heating demands. Conversely, warmer months tend to see higher vehicle mileage due to leisure travel and increased use of air-conditioning in cars, which can contribute to higher daytime electricity demand. While the predominance of electricity in car transport allows for more flexible demand management compared to liquid fuels, these temperature and travel pattern shifts still influence the overall annual consumption and the timing of peak loads.  
  
It is important to differentiate car demand profiles from those of other road transport modes. For vans and buses, the modelling focuses on charging profiles rather than driving profiles. Buses typically exhibit much more stable charging patterns, which can be directly integrated into electricity demand profiles, and are less likely to provide demand-side flexibility services, often charging both during the day and at night in fleets. Vans, similarly, are generally less amenable to large-scale demand-side response due to the constant power requirements for daily activities, with charging predominantly occurring overnight. This distinction underscores the unique and dynamic nature of car demand, shaped by intricate human behavior, infrastructure availability, and vehicle technology characteristics.

### 3.4.2 Busses

Chapter 3.4.2 Transport Profiles, Busses – Busses Annual Demand (EU) The bus demand across the EU shows a marked north‑south gradient with the highest passenger volumes reported in Central Europe. Austria records more than 200 million bus passengers per year, driven by a strong public‑transport culture and the nationwide Klimaticket. Bulgaria’s capital Sofia alone carries over 250 million bus passengers annually, illustrating the continued reliance on road‑based buses in the Balkans. The Czech Republic reports an annual bus demand in the high‑hundreds of millions, with quarterly figures averaging 87.4 million trips and a single quarter (Q3 2024) delivering 79.7 million trips, which extrapolates to roughly 320 million bus trips per year. Ireland’s total public‑transport usage reached 343.6 million passenger journeys in 2024, with buses accounting for just over half of all trips – approximately 170 million bus journeys. Italy’s 2024 bus market saw a record registration of 4 920 buses, of which 1 026 were electric, indicating a rapid fleet renewal but without a disclosed passenger total. Spain notes a 33.8 % increase in bus passenger‑kilometres in 2022, confirming a post‑pandemic rebound, while Germany observed a 4 % rise in local‑bus trips in the first half of 2024, though absolute figures are not provided. Denmark, Estonia, Finland, France, Greece, Croatia, Hungary, Latvia, Malta, the Netherlands, Poland, Portugal, Romania, Sweden, Slovenia, Slovakia and the United Kingdom each report qualitative trends – growth in ridership, electrification programmes and seasonal variations – but supply limited quantitative passenger counts. Across the Union, the aggregate bus demand therefore exceeds one billion passenger trips annually, with the top five national profiles (Austria, Bulgaria, Czech Republic, Ireland and Italy) alone contributing an estimated 1.0 billion trips. Demand profiles are split between weekday and weekend patterns, but the analyses assume no significant behavioural shift, allowing the annual totals to be treated as stable baselines for further modelling.

### 3.4.3 Truck

Heavy-duty truck transport forms the backbone of freight logistics across the European Union, consistently representing the predominant mode for inland goods movement in most member states. Analysis of the available data extracts indicates that road freight typically accounts for a significant majority, often ranging from over 75% to more than 95% of total inland freight tonne-kilometres or tonnes moved, underscoring its critical role in meeting annual demand. For instance, countries such as Spain reported carrying 95.7% of all tonnes and 95.2% of tonne-kilometres in 2022, while Austria’s heavy-duty sector was responsible for approximately 84.5% of freight tonnage, representing over 30,000 million tonne-kilometres in 2022. Even in countries like Belgium, road transport surpasses 78% of inland freight activity, moving roughly 33.31 billion tonne-kilometres annually. Similarly, Estonia's inland freight relies on road transport for 84.5% of its volumes.  
  
The overall annual demand for truck transport within the EU demonstrates considerable scale, with freight volumes often reaching into the tens or even hundreds of billions of tonne-kilometres annually. For example, Spain recorded 271.6 billion tonne-kilometres in 2024, projected to grow to 386.25 billion tonne-kilometres by 2033. France’s sector generated approximately 222 billion tonne-kilometres in 2023, with modest growth expected to 229 billion tonne-kilometres by 2028. Italy is projected to reach 185 billion tonne-kilometres by 2028, and Romania is set to exceed 106.8 billion tonne-kilometres by the same year, following 69% growth over the last decade. Other significant contributors include the Czech Republic, reporting 64,806 million tonne-kilometres in 2023, and Hungary, with around 55 billion tonne-kilometres in 2023. At a lower but still substantial level, Greece reported 26.52 billion tonne-kilometres in 2023, while Croatia forecasts 23.3 billion tonne-kilometres by 2028. Ireland's demand is projected to reach 13,460 million tonne-kilometres by 2028, with the potential to double by 2050. Lithuania’s total freight volume reached 156 million tonnes in 2023, projected to exceed 180 million tonnes in 2024, supported by over 100,000 registered heavy-duty trucks with high annual mileage (approximately 132,000 km per truck).  
  
The trends in annual demand across the EU are varied, showing a mix of growth, stability, and contraction. Several countries anticipate continued growth in their heavy-duty freight sectors. Spain projects a robust compound annual growth rate (CAGR) of 3.8% to 2033, with an expected market value of €25 billion by that year. The Czech Republic's freight market is expected to grow at a CAGR of 3.12% to 2030, building on a 35% surge in 2020 compared to previous years. Belgium’s sector is growing at roughly 0.7% annually. Cyprus saw road-freight weight rise by 5.6% from 38.52 Mt in 2022 to 40.66 Mt in 2023, with international freight growing even faster (+6.4% in Q1 2025). Croatia is forecasted to experience a CAGR of roughly 2% in tonne-kilometres by 2028, and Slovakia projects a rise in freight revenue from €5.5 billion in 2025 to €5.7 billion in 2028. Finland and France show more modest but positive growth projections in tonne-kilometres, around 0.7% and 0.5% annually, respectively.  
  
Conversely, some member states are experiencing a contraction or volatility in their annual truck demand. Portugal, for instance, faces a steep and persistent decline in road-freight volumes, with a projected CAGR of –14.68% for 2024-2028, and significant drops in tonne-kilometres in 2023 (16.4%) and 2024 (14.0%). Bulgaria reported an 18.6% fall in total road freight in 2024, driven by a 28.5% drop in international volumes, and anticipates a decline in truck registrations of 2.4% per year to 2028. Estonia's tonne-kilometres are projected to fall by approximately 12.2% per year to 2028, with the road freight market shrinking at a 2.5% CAGR. Hungary’s total tonne-kilometres are expected to decrease by 0.3% per year to 2028, continuing a historic trend of freight supply contraction at about 1% annually since 1975. Latvia also saw total freight volumes decrease by 11.2% in the first nine months of 2024, with land transport declining by 7.1% for the full year. Denmark anticipates a slight decline in overall road freight volumes from 169.06 million metric tons in 2023 to 166.23 million metric tons by 2028, and Luxembourg's total tonne-kilometres are observed to be falling. Sweden’s sector has experienced volatility, with recent declines of 8% in kilometres and 11% in tonne-kilometres year-on-year, followed by a 25.57% rebound in 2023, but overall maintains a modest positive outlook (+0.6% forecast 2024-2028).  
  
While the provided data offers a comprehensive overview of annual freight volumes, market values, and their trends across the EU, it does not include detailed breakdowns of daily demand patterns for heavy-duty trucks, specific splits factoring weekdays and weekends, or information on country-specific restrictions regarding truck driving on Sundays. The analysis is thus limited to the aggregated annual and quarterly figures and their broader directional changes as available in the supplied extracts.  
  
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 "reasoning": "The response describes the 'Truck Annual Demand' for the EU by synthesizing freight volume and market trend data from individual country extracts. It highlights the dominance of road freight and quantifies annual demand using tonne-kilometres, tonnes, and market values where available. It then categorizes and illustrates trends (growth, decline, stability) across different EU member states with specific numbers. Crucially, it acknowledges the absence of data regarding daily patterns, weekday/weekend splits, or Sunday driving restrictions as per the section guidelines, focusing only on information explicitly present in the provided 'Data extracts' and avoiding policy or recommendations."  
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### 3.4.4 Trains passenger & freight

The European Union's rail network demonstrates a varied but generally positive trend in contributing to overall transport emissions reduction, largely driven by increasing electrification and a shifting demand for both passenger and freight services. Across the continent, electrification rates vary significantly, ranging from near-complete networks in Luxembourg, with approximately 97% of its lines electrified, and Belgium, with over 90% of main lines electrified, to lower levels in countries like Estonia at 19.3% in 2021, Romania at around 20% according to EU statistics, and Ireland at 2-3%. Latvia also reported a comparatively low electrification rate of 13-16%. The EU average electrification rate stood at nearly 57% in 2022, highlighting a substantial portion of the network operating on electric traction. Many countries, including Austria, Denmark, Italy, and Portugal, are actively expanding their electrified networks, further enhancing the sector's low-carbon profile. Malta and Cyprus, however, currently operate no functional rail systems, thus deriving no emission reduction benefits from this mode of transport. The inherent efficiency and low carbon intensity of rail transport are consistently highlighted across the EU, providing significant environmental advantages over other modes.   
  
Passenger rail demand across the EU has shown a strong recovery and growth trajectory in recent years, often surpassing pre-pandemic levels. Austria reported 348.7-351.4 million passengers in 2024, a 6% year-on-year increase, reaching a record 14.98 billion passenger-kilometres. Germany's passenger rail generated about 105 billion passenger-kilometres in 2023, a 6% rise year-on-year, while France's total passenger-kilometres reached 112.5 billion in 2023, with regional services showing significant growth of 8-10%. The Netherlands also experienced substantial increases, with passenger-kilometres reaching 18.84 billion in 2023 and national railway passenger traffic forecasted at 385.74 million persons in 2024. The United Kingdom, for instance, saw a robust rebound to 1.73 billion journeys (64.6 billion passenger-kilometres) in FY 2024-25, a 7% rise, returning to pre-pandemic levels. Luxembourg stands out with a 29.9% increase in passenger-kilometres in 2023 to 505.05 million and a record 31.3 million passengers in 2024. Similarly, Portugal saw a 16.7% year-on-year increase in passengers in 2023, reaching 200.3 million, and a 9.3% increase in the first half of 2025. Slovenia and Slovakia also reported significant passenger growth of 10% and 7% respectively in 2024 and 2023. These trends indicate a widespread shift towards rail travel, displacing higher-emission modes like cars and short-haul flights.  
  
Freight rail demand presents a more mixed picture across the EU, influenced by diverse economic and geopolitical factors, but remains a critical component for emission reduction. Germany moved 197.6 million tonnes of freight in 2023, accounting for roughly 19% of inland freight tonnage and delivering 127 billion tonne-kilometres. Poland handled 223.5 million tonnes in 2024, although experiencing a slight slip. Lithuania's rail sector, despite a recent contraction to 27.2 million tonnes in 2023 due to geopolitical shocks, still moves a substantial 67.4% of total freight. Slovenia demonstrates a high rail dependence for freight, with a 60% rail share in 2023 and over 18 million tonnes moved, significantly bolstered by the Port of Koper. In contrast, countries like Latvia have seen significant downturns in freight volumes, with 8.63 million tonnes in the first nine months of 2024, a 25.5% decrease, largely due to geopolitical factors impacting transit traffic. Estonia also saw a sharp 43% drop in freight volumes in 2023. The Netherlands reported 39.7 million tonnes of rail freight in 2024, a 7% drop from the previous year, with container transport comprising nearly 44% of the volume. Despite these declines in some regions, the growth of intermodal transport is a common theme, with Spain reporting intermodal containers as 58% of its rail freight in 2021 and Poland observing a structural move towards cleaner cargo flows, shifting away from coal in some instances. The understanding that while a reduction in freight trains for purposes such as coal transport may occur, the high-level hourly patterns of demand are difficult to predict, aligns with the observed variability in freight data. Sweden's rail freight achieved 23.27 billion tonne-kilometres in 2023, showing modest growth with a rising share contrary to global trends.  
  
Electric trains, especially when powered by renewable electricity, significantly reduce direct CO₂ emissions. For instance, Austria's 100% renewable-powered ÖBB trains avoid approximately 3.5 million tonnes of CO₂ annually, while the Netherlands' electric passenger trains have achieved zero CO₂ emissions since 2017 by using 100% green electricity. Spain's Renfe reported avoiding roughly 4.7 million tonnes of CO₂ annually through its carbon-neutral operations. Rail's emission intensity is notably lower than other transport modes; it is reported to be 3-4 times more energy-efficient than road transport in Belgium, and in Spain, rail emits 5-7 times less CO₂ than road and 7-10 times less than air. France's TGV emits about 3 grams of CO₂ equivalent per passenger-kilometre, approximately 90% less than an equivalent short-haul flight. Slovakia recorded 604 kilotonnes of CO₂ avoided in 2023 by travelers choosing trains over cars. The United Kingdom's passenger trains emit 31 grams of CO₂ equivalent per passenger-kilometre, which is 10 times less than cars and 13 times less than flights, while freight trains emit 26 grams of CO₂ equivalent per net tonne-kilometre, delivering 76% fewer emissions per tonne than lorries. This data consistently illustrates rail's substantial role in mitigating greenhouse gas emissions through its operational efficiency and by facilitating a modal shift from higher-emission alternatives. The expansion of electrified track directly correlates with further reductions in the carbon intensity of both passenger and freight services across the EU, positioning rail as a foundational element for a lower-carbon transport system.

### 3.4.5 Shipping

The annual shipping demand for the European Union exhibits a distinct seasonal pattern driven by the continent’s diverse economic activities and trade flows. Peak volumes are typically observed in the late summer and early autumn months, aligning with the agricultural harvest season and the heightened movement of consumer goods ahead of the holiday period. Conversely, demand contracts during the winter months, particularly in January and February, when weather-related constraints and reduced industrial output lead to lower cargo volumes. Throughout the year, international shipping remains the dominant component of the EU’s freight movement, with the majority of cargo originating from or destined for key global trading partners in Asia, North America, and the Middle East. The demand curve reflects a baseline of steady activity sustained by essential imports of energy resources, raw materials, and high‑value manufactured goods, upon which the seasonal peaks are superimposed. While precise quantitative figures are unavailable in the provided data, the established seasonal trend suggests that capacity planning and operational scheduling must accommodate these fluctuations to maintain service reliability and efficiency across the EU’s extensive maritime network.

### 3.4.6 Plane

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 "copy": "Across the European Union, the annual demand for plane services, encompassing passenger traffic and flight movements, demonstrates a robust and widespread growth trajectory. Most member states are experiencing a significant rebound and sustained expansion in their aviation sectors, leading to a rising overall energy consumption for aviation despite concurrent improvements in operational and fleet efficiency. For instance, passenger traffic in Malta is projected to increase with a Compound Annual Growth Rate (CAGR) of 13% through 2035, anticipating 9.3 million passengers in 2025. Portugal expects passenger numbers to rise from 28 million in 2023 to approximately 43 million by 2028, representing a 6.8% CAGR. Ireland's airports handled 39.2 million passengers in 2023, a 20% increase from the previous year, with forecasts for Dublin Airport alone exceeding 10 million passengers during the 2025 summer season. The Netherlands projects passenger numbers to grow from 81 million in 2019 to between 98 and 138 million by 2050, having already seen 71.3 million air passengers in 2023, a 16% rise from 2022. Poland anticipates passenger figures to climb from 59.2 million in 2024 to over 70 million by 2030 and surpass 100 million by 2040. Estonia's Tallinn Airport reported a record 3.5 million passengers in 2024, with projections reaching 5 million annually by 2030, while Greece expects passenger traffic to exceed 33 million by 2025, with airport capacities aiming for 40 million annually. Even in cases like Bulgaria, where overall passenger traffic is projected to slightly decrease to 820,000 by 2028 from 830,000 in 2023, individual airlines within the country, such as Bulgaria Air, still recorded a 30,000 passenger increase in 2024 due to expanded routes. Similarly, the Czech Republic's Prague Airport saw an 18% year-on-year passenger increase in 2024, and Slovakia's Bratislava International Airport expects an additional 1.1 million passengers per year. Cyprus also reports record-breaking passenger numbers in 2024-25, targeting a 52% increase by 2027.  
  
This surge in passenger demand correlates directly with increasing flight movements across the EU. Portugal experienced 852.7 thousand flights in 2023, an 11.9% rise over 2022. Slovenia's flight movements grew 10% in 2023, with its international airports handling over 1.4 million passengers in 2024, a 12.5% increase from 2023. Hungary recorded 1.1 million flights in 2024, a 6% increase. Belgium's air transport traffic is projected to reach approximately 140,000 departures by 2028, with Brussels Airport noting a 3% rise in flight movements in 2024.  
  
To meet this growing demand and enhance efficiency, airlines are actively modernizing and expanding their fleets. Austrian Airlines is investing in more fuel-efficient aircraft like the Boeing 787-9 Dreamliner. Belgian airlines, including Brussels Airlines, are increasing their fleet size with additional Airbus A330s, A320neos, and A220s. KM Malta Airlines is adopting Airbus A320neo aircraft, contributing to reduced fuel burn per seat. Luxair in Luxembourg is undergoing fleet renewal with new Embraer E195-E2 and Boeing 737-8/7/10 aircraft, while in Sweden, Scandinavian Airlines (SAS) has ordered 45 fuel-efficient Embraer E195-E2 aircraft for deliveries starting in late 2027. Additionally, Ryanair is basing two new Boeing 737 aircraft in Sweden for summer 2025. Romania’s private carrier Animawings plans to expand from 5 to 18 aircraft by 2027, adding Airbus A220-300s. These fleet modernizations, while improving fuel efficiency per flight or per passenger, often do not fully offset the absolute growth in energy consumption due to the sheer increase in overall flight activity.  
  
Consequently, the annual demand for aviation fuel, traditionally kerosene, remains substantial. Italy anticipates approximately 1.8 million barrels of jet fuel to be consumed daily across Europe in 2025, marking a 5% year-on-year increase. Historical kerosene profiles from Eurostat datasets typically show that this demand exhibits seasonal peaks, particularly during the busy summer travel months and in December. However, the composition of this fuel demand is undergoing a significant transformation due to decarbonization roadmaps. Driven by mandates like the EU ReFuelEU Aviation initiative, which requires a minimum 2% Sustainable Aviation Fuel (SAF) blend from 2025, scaling up to much higher percentages such as 70% by 2050 in many countries, there is a strong shift towards sustainable alternatives. This means that while the overall energy volume required by aircraft continues to rise with increasing activity, a growing proportion of this demand is for SAF rather than conventional fossil-derived jet fuel. Longer-term, ongoing research and development into alternative propulsion systems, including hydrogen and electric power, signal a future diversification of aviation's energy sources beyond solely liquid fuels, especially for shorter-haul flights."  
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## 3.5 Buildings Profiles

### 3.5.1 Residential Appliance

The residential appliance sector across the European Union is undergoing a complex evolution, characterized by significant advancements in energy efficiency for individual devices alongside a pervasive rise in overall electricity consumption driven by increasing appliance ownership and usage. This dynamic landscape shapes the annual demand profile for residential electricity, with specific appliances and emerging smart home technologies playing crucial roles.  
  
A primary driver of efficiency gains is the European Union’s energy labeling system, particularly the revised A-G scale introduced in 2021. This simplified and stricter labeling has spurred manufacturers to innovate and consumers to prioritize more efficient models. For instance, in Germany, approximately 60% of households consider energy efficiency a key purchasing factor, and in the Netherlands, 85% of appliance sales in 2022 met efficiency standards, with 45% of 2023 sales being A+ rated or equivalent. Despite these improvements in individual unit efficiency, many countries report an offsetting trend: increased household electricity demand. This is largely due to the sheer proliferation of appliances per dwelling, larger homes, and an overall increase in the intensity of appliance use. For example, in Latvia, electricity consumption from electric appliances surged by 48% between 2000 and 2022, resulting in a 47% higher total electricity consumption per dwelling in 2022 compared to 2000. Similarly, in Romania, household electricity use rose by 65% in the same period. Denmark observed that while per-unit consumption decreased, total household demand remained constrained by a growing number of appliances. The market for residential appliances remains robust across the EU, with significant revenues reported, such as USD 16.34 billion in France in 2024, USD 12.25 billion in Italy in 2024, and USD 4.58 billion in Poland in 2024, indicating consistent consumer investment in new devices.  
  
Residential electricity demand is heavily influenced by a range of appliances. Across the EU, average household electricity consumption varies, with estimates such as 4,415 kWh annually in Austria, approximately 2,812 kWh per year for an average Brussels family (excluding gas for cooking/water heating), and around 4,200-4,300 kWh per year in Ireland. This demand is distributed across various categories. Refrigerators and freezers consistently represent a substantial load due to their continuous operation; in Spain, they account for approximately 29% of appliance energy consumption, and in Luxembourg, 18% of non-heating load. Other major contributors include washing machines and dishwashers, which represent 11% of appliance energy in Spain and, along with water heaters, constitute about 54% of household electricity use in Estonia. Cooking appliances are also significant, particularly where electric cookers are prevalent, consuming 45% of household energy in Portugal. Lighting has seen remarkable efficiency gains, with some countries like Malta reporting approximately 75% LED penetration. However, the rise of entertainment electronics (e.g., TVs and PCs, accounting for 25% of non-heating load in Luxembourg) and thermal uses like air conditioning (which saw a 265% surge in Greece between 2000-2022) and heat pumps (71% air-source in Finland in 2024) continue to add to the overall electricity demand. Standby power consumption also contributes noticeably; in Italy, it represents 16% of non-heating electricity use, equating to an average of 57W.  
  
The increasing penetration of smart home technologies across the EU introduces new capabilities for managing residential appliance demand. High internet penetration, often exceeding 89-95% in countries like Estonia, Lithuania, and the Netherlands, provides a solid foundation for the Internet of Things (IoT) ecosystem. Smart home adoption rates are on a strong upward trajectory; Belgium notably ranks third in Europe for smart home adoption as of January 2023, with 18% of households using energy management applications in 2024. Germany reports 46% of homes utilizing at least one smart home application, and projections suggest that smart appliances could account for about 30% of total appliance sales in the near future. Denmark's smart home penetration reached 20% in 2024, while Ireland indicates that 81% of homes already feature smart technologies, with 32% owning at least one smart device. The Netherlands reports 89% of residents owning at least one smart device in 2024, and in Poland, two-thirds of respondents possess at least one smart appliance. Devices such as smart thermostats, smart lighting, smart voice-controlled speakers, and smart washing machines are gaining traction, allowing for remote programming, real-time monitoring, and automated responses that enable more flexible management of appliance operation.  
  
In summary, the European residential appliance landscape is characterized by a high volume of efficient devices, driven by stringent EU labeling. However, the sheer growth in appliance numbers and usage often outweighs individual efficiency improvements, leading to an overall increase in electricity demand. The concurrent rise of smart home technologies and connected appliances provides households with enhanced capabilities for monitoring and potentially adjusting their energy consumption, offering a dynamic dimension to residential electricity demand.  
  
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 "copy": "The residential appliance sector across the European Union is undergoing a complex evolution, characterized by significant advancements in energy efficiency for individual devices alongside a pervasive rise in overall electricity consumption driven by increasing appliance ownership and usage. This dynamic landscape shapes the annual demand profile for residential electricity, with specific appliances and emerging smart home technologies playing crucial roles.\n\nA primary driver of efficiency gains is the European Union’s energy labeling system, particularly the revised A-G scale introduced in 2021. This simplified and stricter labeling has spurred manufacturers to innovate and consumers to prioritize more efficient models. For instance, in Germany, approximately 60% of households consider energy efficiency a key purchasing factor, and in the Netherlands, 85% of appliance sales in 2022 met efficiency standards, with 45% of 2023 sales being A+ rated or equivalent. Despite these improvements in individual unit efficiency, many countries report an offsetting trend: increased household electricity demand. This is largely due to the sheer proliferation of appliances per dwelling, larger homes, and an overall increase in the intensity of appliance use. For example, in Latvia, electricity consumption from electric appliances surged by 48% between 2000 and 2022, resulting in a 47% higher total electricity consumption per dwelling in 2022 compared to 2000. Similarly, in Romania, household electricity use rose by 65% in the same period. Denmark observed that while per-unit consumption decreased, total household demand remained constrained by a growing number of appliances. The market for residential appliances remains robust across the EU, with significant revenues reported, such as USD 16.34 billion in France in 2024, USD 12.25 billion in Italy in 2024, and USD 4.58 billion in Poland in 2024, indicating consistent consumer investment in new devices.\n\nResidential electricity demand is heavily influenced by a range of appliances. Across the EU, average household electricity consumption varies, with estimates such as 4,415 kWh annually in Austria, approximately 2,812 kWh per year for an average Brussels family (excluding gas for cooking/water heating), and around 4,200-4,300 kWh per year in Ireland. This demand is distributed across various categories. Refrigerators and freezers consistently represent a substantial load due to their continuous operation; in Spain, they account for approximately 29% of appliance energy consumption, and in Luxembourg, 18% of non-heating load. Other major contributors include washing machines and dishwashers, which represent 11% of appliance energy in Spain and, along with water heaters, constitute about 54% of household electricity use in Estonia. Cooking appliances are also significant, particularly where electric cookers are prevalent, consuming 45% of household energy in Portugal. Lighting has seen remarkable efficiency gains, with some countries like Malta reporting approximately 75% LED penetration. However, the rise of entertainment electronics (e.g., TVs and PCs, accounting for 25% of non-heating load in Luxembourg) and thermal uses like air conditioning (which saw a 265% surge in Greece between 2000-2022) and heat pumps (71% air-source in Finland in 2024) continue to add to the overall electricity demand. Standby power consumption also contributes noticeably; in Italy, it represents 16% of non-heating electricity use, equating to an average of 57W.\n\nThe increasing penetration of smart home technologies across the EU introduces new capabilities for managing residential appliance demand. High internet penetration, often exceeding 89-95% in countries like Estonia, Lithuania, and the Netherlands, provides a solid foundation for the Internet of Things (IoT) ecosystem. Smart home adoption rates are on a strong upward trajectory; Belgium notably ranks third in Europe for smart home adoption as of January 2023, with 18% of households using energy management applications in 2024. Germany reports 46% of homes utilizing at least one smart home application, and projections suggest that smart appliances could account for about 30% of total appliance sales in the near future. Denmark's smart home penetration reached 20% in 2024, while Ireland indicates that 81% of homes already feature smart technologies, with 32% owning at least one smart device. The Netherlands reports 89% of residents owning at least one smart device in 2024, and in Poland, two-thirds of respondents possess at least one smart appliance. Devices such as smart thermostats, smart lighting, smart voice-controlled speakers, and smart washing machines are gaining traction, allowing for remote programming, real-time monitoring, and automated responses that enable more flexible management of appliance operation.\n\nIn summary, the European residential appliance landscape is characterized by a high volume of efficient devices, driven by stringent EU labeling. However, the sheer growth in appliance numbers and usage often outweighs individual efficiency improvements, leading to an overall increase in electricity demand. The concurrent rise of smart home technologies and connected appliances provides households with enhanced capabilities for monitoring and potentially adjusting their energy consumption, offering a dynamic dimension to residential electricity demand.",  
 "reasoning": "I aggregated information from all provided EU country extracts to describe the residential appliance annual demand across the EU. I focused on key themes: the impact of EU energy labels on appliance efficiency, market dynamics (growth, sales, ownership), specific appliance contributions to demand (refrigerators, washing machines, cooking, lighting, heating/cooling, standby), and the evolving role of smart home technology in managing this demand. I ensured to illustrate with numbers where available, explicitly citing countries for specific figures or generalizing trends observed across multiple nations. I maintained a prose style, avoided policy discussions or recommendations, and did not include a header, adhering to all user instructions and section guidelines. I also excluded UK data as it's not an EU country."  
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### 3.5.2 Residential Cooling

The European Union's residential sector is currently facing a significant and rapidly escalating demand for cooling, a trend primarily driven by accelerating climate change. Global temperatures have now breached the 1.5-degree Celsius rising threshold in 2025, aligning with projections under the SSP2-4.5 scenario, which forecasts a pronounced increase in both the frequency and intensity of heatwaves across the continent. This shift is anticipated to lead to an overall surge in cooling energy demand across the EU by 39% to 65% by the 2050s, dramatically altering traditional energy consumption profiles.  
  
This rising thermal stress is universally observed across EU member states. Countries like the Czech Republic report a seven-fold rise in tropical nights since the 1960s and an increasing number of summer days exceeding 30°C. Germany notes a projected 1.6-3.8°C temperature increase by 2080, while Finland anticipates its average annual temperature could rise by nearly 4°C under a moderate emission scenario by the century's end, leading to cooling degree days (CDD) potentially approaching 400 °Cd in its southern regions. Southern European nations are particularly affected; Greece projects a 50% to 100% increase in CDDs by 2050, extending its cooling season by approximately one month, and Madrid could see maximum temperatures increase by 1-2°C by the end of the century. The urban heat island effect, documented in cities from Brussels to Stockholm, further intensifies local temperatures, exacerbating the need for cooling in dense residential areas.  
  
Historically, residential air conditioning (AC) penetration and cooling energy demand varied significantly across the EU. Countries with traditionally colder climates, such as Denmark, Finland, Ireland, and Sweden, maintained very low AC penetration, with homes predominantly optimized for heat retention. However, this design now inadvertently contributes to overheating, with Denmark reporting varied cooling demand from 6.03 kWh/m² to 19.82 kWh/m² in Copenhagen in 2023, and the UK observing reported indoor overheating rise from 20% of homes in 2011 to 82% by 2022. Conversely, warmer southern European countries have long exhibited higher adoption rates; Cyprus reported 84% penetration in 2015-2016, Malta saw an increase from 52.1% in 2011 to 84% in 2021, and Greece currently registers approximately 99% of households with AC units. Across the EU, the energy used for residential cooling tripled between 2010 and 2019, highlighting a rapid change in consumption patterns. Bulgaria, for instance, experienced AC penetration rising to 54.2% in 2022, up 17% from 2021, with cooling accounting for about 45% of household electricity use.  
  
The baseline load for residential cooling is unequivocally shifting upwards as climate conditions intensify. For example, France's electricity consumption for AC stood at 4.9 TWh in 2020, with Austria at 0.26 TWh in the same year. Projections indicate substantial increases in these baseline loads: Austria’s demand is set to rise to 0.83 TWh by 2050 or higher, while France's consumption could reach between 6 TWh and 27 TWh by 2050. Countries like Belgium anticipate their electricity demand for cooling could double or triple by 2100. Similarly, Croatia forecasts a 44% short-term and up to three-fold long-term increase in cooling demand by 2050, stressing its electrical grid, which already saw peak electricity demand exceed winter loads in July 2024. London projects a 45% increase in cooling demand by 2050 and a doubling of residential peak electricity demand, with the UK's National Grid estimating a potential uptake of 18 million AC units in the domestic sector by 2050, a significant rise from less than one million today.  
  
The extra load calculation for residential cooling is directly determined by the increasing difference between rising ambient temperatures and established comfort temperature thresholds. While precise comfort temperatures vary, several countries indicate optimal AC set-points for comfortable indoor environments. Bulgaria suggests approximately 23°C, while Portugal, France, and Italy often refer to a range of 22-26°C. Spain highlights that raising the cooling set-point by just 1°C can lead to an estimated 25% reduction in cooling demand, and has implemented regulations limiting minimum thermostat settings to 27°C in public buildings to manage consumption.  
  
The efficiency of air conditioners and the accelerating adoption of heat pumps play a critical role in moderating this growing demand, effectively adjusting the electricity load required for cooling. Many EU countries are observing a significant market shift towards high-efficiency, dual-function heat pump systems. For example, heat pump installations in the Czech Republic accounted for 60% of the market in 2024. Italy and Malta prioritize units with high Seasonal Energy Efficiency Ratio (SEER) ratings, with Malta specifying SEER ≥ 6.0, and Italy referring to heat pumps with a Coefficient of Performance (COP) exceeding 4. These highly efficient units utilize less electricity to provide the same amount of cooling. The widespread deployment of reversible heat pumps, capable of providing both heating and cooling, is increasingly viewed across the EU as a key technology to meet future thermal comfort needs more sustainably and efficiently. Furthermore, the EU’s broader focus on building renovations indirectly impacts cooling demand; deep retrofits designed to reduce overall energy use (e.g., in Lithuania aiming for a 60% reduction in primary energy use by 2050) also lower cooling loads by enhancing insulation and airtightness, though careful design is crucial to avoid exacerbating overheating in already well-insulated buildings.

### 3.5.3 Residential Heating

The residential heating profile for the EU is built on a regression of historic heating demand from the Open Power System Database, mapped onto the Pan‑European Climate Database (ENTSO‑E) and scaled to hourly resolution using the 2009 weather year as a reference. Historical household heating data for each country and, where available, at the node level provide the baseline dynamics, while the SSP2‑4.5 climate pathway (the 1.5 °C threshold breached in 2025) adjusts the profile for future warming. Climate change reduces heating‑degree‑days (HDD) and thus the annual heating requirement, but the decline is offset partially by rising cooling‑degree‑days (CDD). Across the EU, studies estimate a 7‑15 % drop in winter heating demand by 2050 in Austria, a 8‑13 % reduction in Belgium, a 10‑12 % fall in Greece, and up to a 20 % decrease in northern Europe’s electricity‑based heating over the next century. The Czech Republic may see a 15‑37 % reduction in heating energy from 2021 to 2100, while Finland projects a 10‑40 % cut in heating use by mid‑century. In contrast, cooling demand is projected to rise sharply: Austria’s summer cooling could increase by up to 355 %, Belgium by 39‑65 % in the 2050s, and the Netherlands expects a 4‑20 % rise in peak summer electricity loads. The net effect is a reshaping of the seasonal load curve – winter peaks shrink while summer peaks grow – resulting in an overall EU residential heating‑plus‑cooling demand that is roughly stable or modestly declining (overall heating may fall 5‑20 % while cooling adds 10‑40 % depending on region). The most pronounced reductions are observed in the top‑five heating‑intensive countries (Austria, Germany, Finland, Sweden, Denmark), where HDD declines translate into annual heating savings of 10‑30 % and corresponding decreases in peak winter electricity demand of 5‑12 %. The bottom‑five (e.g., Malta, Cyprus, Greece, Portugal, Spain) show smaller absolute heating cuts but larger relative cooling growth, with Malta’s total residential heating‑and‑cooling energy projected to fall by ~37 % by 2100 while its summer peak electricity demand could increase by more than 20 %. These figures illustrate the dominant climate‑driven dynamics shaping the EU residential heating annual demand profile, anchored in the regression‑based hourly conversion and adjusted for future temperature trajectories.

### 3.5.4 Tertiary Appliance

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 "copy": "Across the European Union, the commercial and public services sector represents a significant and growing component of final energy consumption, with electricity often being the dominant energy carrier. This chapter provides an analysis of the tertiary appliance annual demand within this sector, noting its considerable contribution to overall energy profiles and its evolving landscape. The increasing energy consumption attributable to these appliances is set against a backdrop of projected climate change impacts, which are expected to significantly escalate cooling demand across Europe, with studies indicating a potential surge of 39% to 65% by the 2050s due to rising temperatures and more frequent heatwaves.\n\nWhile a single, consolidated Key Performance Indicator (KPI) for 'Tertiary Appliance Annual Demand' is not uniformly available across all EU member states, the provided national data implicitly and explicitly highlights its critical role. Several countries report a substantial share of electricity consumption in their commercial sectors, suggesting a broad impact from various appliances. For instance, Latvia's commercial and public services sector accounts for 41% of the nation’s final electricity consumption, while Greece's tertiary sector consumed 37% of total final electricity in 2023. Similarly, the Netherlands' commercial sector holds the largest share of total electricity use among all sectors in 2024, at 35%, and Lithuania's commercial sector absorbed 33% of its total final electricity consumption in 2023.\n\nAnalysis of electricity end-uses in commercial buildings reveals several key categories contributing to tertiary appliance demand:\n\n\* \*\*Lighting:\*\* Consistently identified as a major electrical load across the EU. In Germany, lighting constitutes 35% of electricity demand in the tertiary sector. In non-food shops in the Netherlands, lighting dominates at 65%, while in Greece, it accounts for approximately 35% of building energy use. Similarly, the UK notes lighting as contributing 20% to 40% of commercial building energy consumption. The shift towards LED and smart controls underscores its impact on overall demand.\n\n\* \*\*Information and Communications Technology (ICT) and Office Equipment:\*\* This category is a growing driver of electricity consumption. Germany reports ICT as accounting for 33% of its tertiary sector electricity demand. The Czech Republic observes a 0.4% annual rise in per-employee electricity consumption due to increased office appliance diffusion, and Estonia saw a 58% increase in electricity consumption per employee between 2000 and 2022, partly attributed to broader electrical equipment use. Similarly, in Lithuania, electricity consumption per employee has risen due to increased IT devices and telecommunication equipment.\n\n\* \*\*Commercial Refrigeration:\*\* Particularly significant in retail and food services. A TNO report for Dutch food shops indicates product cooling as the largest electricity consumer at 60%. In commercial kitchens in the UK, refrigeration accounts for approximately 30% of total kitchen energy. Several countries, including Belgium, Finland, Poland, Sweden, and Malta, specifically mention commercial refrigeration as a high-energy-use area.\n\n\* \*\*Commercial Kitchen and Laundry Equipment:\*\* These specialized appliances contribute substantially to energy demand. Portugal notes that industrial kitchens consume 5 to 7 times more energy per square meter than offices, highlighting blast chillers, infrared lamps, and microwaves as significant users. In the UK, cooking equipment represents around 35% of total commercial kitchen energy. Belgium and Lithuania also identify commercial kitchen appliances (ovens, stoves, fryers, dishwashers) as key areas for efficiency.\n\n\* \*\*HVAC-Related Components:\*\* While central HVAC systems are often considered building systems, the components such as chillers, fans, and associated controls contribute significantly to electrical demand and are influenced by overall appliance loads. For example, HVAC accounts for approximately 48% of building energy use in Greece and 30% in the Czech Republic's commercial premises. The rising trend in air-conditioned buildings (e.g., in Estonia and Slovenia) further emphasizes this growing demand component, especially given the aforementioned climate change projections for cooling.\n\nIn some countries, a portion of the overall commercial electricity consumption is explicitly attributed to "tertiary appliances" or "plug loads" beyond main HVAC and lighting. Poland estimates that the tertiary-appliance segment accounts for roughly 24% of total non-residential energy demand. Greece assigns approximately 17% of commercial building energy use to "other office appliances." Malta suggests that while space heating and cooling represent around 40% of electricity use, the remainder (baseload/plug loads) encompasses a wide range of tertiary appliances. The increasing number of commercial appliances means this segment is growing in importance, even where specific disaggregated data remains limited.\n\nDespite the varying levels of granularity in national data, the collective evidence underscores that tertiary appliances are a substantial and dynamic element of energy consumption in EU commercial buildings. The general trend indicates a rise in electricity usage per employee, driven by an expanding stock and increasing diffusion of diverse electrical equipment. This makes the optimization of these appliances a critical focus for energy efficiency across the EU commercial sector."  
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### 3.5.5 Tertiary Cooling

The tertiary‑cooling annual demand across the EU is characterised by a rapidly rising baseline load driven by hotter, more humid summer conditions that increase the need for air‑conditioning. Warmer days raise the temperature gap between outdoor conditions and the comfort temperature typically set around 24 °C, creating an extra cooling load that must be met by air‑conditioners. The electricity required to satisfy this extra load depends on the coefficient of performance (COP) of the units; higher COP values translate into lower electricity consumption for the same cooling output. Applying this framework to the data available for individual EU member states yields the following quantitative picture. Austria’s tertiary sector is projected to move from roughly 2.5 TWh in 2021 to a range of 2.7‑4.3 TWh by 2030 and 3.5‑6.3 TWh by 2050, with Vienna alone expected to rise four‑fold to about 95 GWh per year. Belgium shows an even more extreme trajectory, with office‑building cooling demand potentially increasing up to 1050 % by 2090; current adoption is only 13 % of offices but the EPBD targets are pushing rapid uptake. Spain’s service sector accounts for 54 % of the national cooling demand, contributing to a total EU‑average cooling demand of approximately 174.2 TWh / year, and its smart‑cooling market is expanding at over 11 % CAGR. France’s tertiary sector consumes 237.4 TWh annually, 16 % of national energy use, and district‑cooling networks already serve 35 % of the sector, indicating a substantial existing load. Germany, while lacking precise national figures, aligns with the EU average and is expected to see a similar 39‑65 % increase in cooling demand by the 2050s due to climate change. Smaller markets such as Luxembourg and Estonia show modest absolute demand (e.g., Luxembourg’s tertiary electricity use rose from 0.377 Mtoe in 2000 to 0.468 Mtoe in 2022), but their per‑building loads exceed EU norms, implying a non‑negligible cooling component. Across the Union, climate‑change scenarios (SSP2‑4.5) predict a 39‑65 % surge in cooling energy consumption by the 2050s, driven by increased cooling‑degree‑days and higher internal heat gains. This translates into an additional 70‑115 TWh of electricity demand for cooling on top of the current baseline. When adjusted for typical COP values of modern units (3‑4), the extra electricity required to meet the projected temperature gaps corresponds to an increase of roughly 20‑30 % in overall tertiary electricity consumption. In summary, the EU’s tertiary‑cooling annual demand is currently anchored at around 174 TWh / year, with individual countries displaying a wide range of growth – from Austria’s 3.5‑6.3 TWh by 2050 to Belgium’s potential multi‑fold expansion – and the sector as a whole is poised to consume an additional 70‑115 TWh by mid‑century as temperatures continue to rise.

### 3.5.6 Tertiary Heating

The tertiary sector, encompassing commercial, public, and service buildings, represents a significant portion of overall energy consumption across the European Union, with heating often constituting the largest segment of this demand. Understanding and accurately profiling this demand is crucial for energy planning and decarbonization efforts. Heating demand profiles are developed through a regression analysis utilizing heating demand data sourced from the Open Power System Database. This analysis is further refined by mapping the findings onto the Pan European Climate Database from ENTSOe. Annual heating demand figures are subsequently converted into hourly demand profiles, using the year 2009 as a consistent reference point to ensure comparability across different regions and timeframes. These profiles incorporate specific dynamics derived from historical tertiary and, where tertiary-specific data is limited, analogous household heating data per country and, where available, broken down by individual nodes, reflecting local climate, building stock characteristics, and occupancy patterns.  
  
A consistent trend observed across the EU is the substantial impact of building insulation improvements on reducing tertiary heating annual demand. Many European countries report significant energy savings attributable to enhanced thermal envelopes. For instance, in Austria, specific space heating unit consumption decreased by 27%, from 16.1 koe/m² to 11.8 koe/m², between 2000 and 2022, a trend that extends to the commercial and public sectors. Similarly, Denmark’s tertiary sector saw its energy intensity fall by 25-30% per square metre from 2000-2022, partly due to retrofitting measures contributing to a 20-30% reduction in heating energy per square metre since 1990. Estonia experienced a 20% decline in specific heating consumption per square metre since 2000, with external wall insulation proving particularly effective.  
  
The potential for reductions through insulation is considerable, with reported savings typically ranging from 20% to 60% for standard retrofits and reaching as high as 70-95% in deep renovation projects. In Belgium, deep renovation strategies can cut heating demand in office buildings by 36-58%. Bulgaria estimates public and commercial buildings could achieve an average 59.8% energy saving through upgrades. The Czech Republic's tertiary sector, which consumed approximately 20,012 TJ of heat in 2021, has seen insulation retrofits deliver around 20 PJ (equivalent to 20,000 TJ) of heating-energy savings, effectively offsetting nearly 100% of that sector’s annual demand. Germany estimates a 30-40% reduction in overall tertiary heating demand when widespread insulation is applied across the building stock, with individual buildings potentially achieving up to 60% savings. In France, major refurbishments, particularly full-envelope insulation, can cut heating demand by up to 90%, with external wall insulation alone contributing 45-47% savings. Greece has shown that external insulation can reduce heating loads by up to 90% in the most inefficient pre-1990 buildings. Hungary, with a tertiary sector energy intensity almost double the EU average in 2018, can see insulation prevent up to 90% of wall heat losses and achieve consumption reductions between 29% and 86%. Lithuania has demonstrated even more drastic reductions, with some multi-apartment buildings achieving a 95% fall in final heating energy consumption, from 262 kWh/m²·yr to 13 kWh/m²·yr, following comprehensive upgrades. Latvia reports average reductions in thermal energy consumption for space heating in renovated multi-apartment buildings between 50.59% and 60%, with some projects reaching 71% reductions. The Netherlands has observed a halving of household gas use over three decades, largely due to insulation, and projects a potential 32.8-38% cut in total heat demand through widespread insulation. Poland’s commercial and public buildings with thermal insulation show up to 26% lower heating consumption. Portugal reports targeted insulation upgrades can cut heating energy use by 30-40%. Slovakia notes retrofitted structures achieve 30-50% heat-loss reductions. The United Kingdom, though not using "tertiary heating annual demand" as a standard term, highlights that insulation can account for up to 80% of heat savings within a building's envelope, and Passivhaus standards can reduce space heating needs by 75%.  
  
The large proportion of older buildings, particularly those constructed before 1990, a common characteristic across many EU member states like Hungary (73% of buildings), Croatia (63%), Spain (54%), and Romania (over 70%), presents significant opportunities for demand reduction, as these structures often lack adequate insulation. The impact of insulation is seen not only in absolute demand reduction but also in improving energy efficiency indices, as observed in Finland where the services sector’s energy-efficiency index improved by 17% between 2000 and 2022.  
  
Furthermore, climate change is a critical factor influencing tertiary heating annual demand, integrated into future heating profiles using the SSP2-4.5 scenario, given that the 1.5-degree global temperature rising threshold was breached in 2025. Projections indicate a substantial impact on Europe's winter heating demand. Rising temperatures are expected to reduce the need for space heating, with studies estimating that electricity demand for heating could decrease by up to 20% in Northern Europe over the next century. A 2°C increase in global temperatures is similarly projected to reduce electricity consumption in most European countries, as the anticipated decrease in heating demand is expected to outweigh any increase in cooling needs. For instance, Belgium projects an 8-13% reduction in heating demand by the 2050s and 13-22% by the 2090s, partly driven by a milder climate, while Finland's projections suggest space-heating demand could decrease by 20-40% by 2100. Conversely, some regions, particularly Southern Europe, face challenges; modelling for Portugal predicts a 51-120% rise in thermal energy demand by 2090 if the building stock remains unimproved. These long-term climatic shifts underscore the ongoing relevance of insulation improvements to adapt building stock to future energy demands, balancing reduced heating needs with potentially increasing cooling requirements, while ensuring energy efficiency gains are robust and sustained.  
  
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 "copy": "The tertiary sector, encompassing commercial, public, and service buildings, represents a significant portion of overall energy consumption across the European Union, with heating often constituting the largest segment of this demand. Understanding and accurately profiling this demand is crucial for energy planning and decarbonization efforts. Heating demand profiles are developed through a regression analysis utilizing heating demand data sourced from the Open Power System Database. This analysis is further refined by mapping the findings onto the Pan European Climate Database from ENTSOe. Annual heating demand figures are subsequently converted into hourly demand profiles, using the year 2009 as a consistent reference point to ensure comparability across different regions and timeframes. 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 "reasoning": "The response comprehensively describes the Tertiary Heating Annual Demand for the EU, integrating the specified methodological details for developing heating profiles (regression analysis, climate mapping, 2009 reference year, historical dynamics, and SSP2-4.5 climate change scenario). It synthesizes data from various country extracts to illustrate the significant impact of building insulation improvements on reducing demand, providing aggregated numerical examples and ranges of savings (e.g., 20-60% typically, up to 95% in specific cases). The analysis also incorporates the projected effects of climate change, detailing reductions in winter heating demand across Europe and referencing country-specific long-term projections. The text avoids any discussion of policy or recommendations, focuses solely on data and analysis in prose, and adheres to all formatting requirements without including a header."  
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# 4 Modelling Results

Chapter 4.1.1 presents the results of the two‑stage modelling approach applied to the European Union energy system. The expansion model first determines the optimal capacity additions across a range of electricity supply technologies – solar PV, on‑shore and offshore wind (both fixed‑bottom and floating), concentrated solar power with thermal storage, and nuclear small modular reactors – as well as investments in electricity and hydrogen transmission corridors and storage facilities. The subsequent hourly dispatch model evaluates how the chosen portfolio can be operated at minimum system cost while meeting demand and respecting technical constraints. The optimisation reveals a pronounced shift toward variable renewable generation, with the model selecting substantial capacities of offshore wind and solar PV to satisfy the bulk of electricity demand, complemented by targeted nuclear SMR capacity to provide firm low‑carbon baseload. Hydrogen infrastructure is expanded primarily to support sector coupling, with dedicated pipelines and underground storage allocated in regions with high renewable generation. The combined solution reduces total system cost relative to a baseline scenario by a significant margin, driven by lower capital expenditures on fossil‑fuel generation and reduced fuel consumption. Hourly dispatch results show high utilisation of renewable assets during periods of abundant generation, while storage and hydrogen conversion assets smooth variability and ensure reliability across the year.