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BUILDING A LOW-CARBON, CLIMATE RESILIENT FUTURE: SECURE, CLEAN AND EFFICIENT ENERGY

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Contents

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Executive Summary

Energy system planning models must improve to ensure greater applicability in decision-making processes. Users of energy system model results have highlighted the need for models to have a holistic and systemic perspective, to be designed to support policy decisions, to strive for maximum transparency, and to involve stakeholders in model design. Here, we detail developments made to three different energy system planning models in light of these user needs, focussing on technologies which could be critical to the energy transition, focus on assessment of policy options and impacts, and transparency in data inputs and model implementation. The models are Euro-Calliope, EnergyPLAN, and IMAGE. Each model differs in focus, both in the scale and resolution of problems considered and the research questions they are best placed to answer. However, they all suffer from some combination of shortcomings required to match user needs. The model developments we detail in this deliverable include sector-coupling in Euro-Calliope, carnot batteries and emissions disaggregation in EnergyPLAN, and increased transparency and use of policy-relevant scenarios in IMAGE. Not only do these developments improve model applicability, they also help to harmonise models for planned intra- and inter-module linkages. Moving forward from this deliverable, further developments are planned for each model within the context of the SENTINEL project to improve technology representation, increase transparency, and facilitate data transfer between models across the SENTINEL consortium.

Introduction

Work Package 4 of the SENTINEL project is concerned with the advancement of the state-of-the-art in energy system planning. In this module, we have found that enabling model linkage is the next paradigmatic step in energy system design (Chang et al., 2020). This linkage is only possible with better understanding between modelling teams on vocabulary, scope, and input datasets. Linkage also requires that models are aligned in the user needs they address. In this deliverable, we are concerned with model development to address user needs. Models developed in this way will be better aligned for linkage in later stages of the SENTINEL project and will be more useful to users of model results as decision-making tools. In this deliverable, we first outline each of the three SENTINEL energy system models, highlighting their key components and differences. We then describe identified user needs and research questions based on the result of surveys, interviews, and workshops undertaken within the SENTINEL project. In light of these user needs, we then detail model developments to address identified user needs and to prepare models to answer relevant research questions. We will finish by discussing the next steps in model development and the linkage between models in this module, as well as to models in other modules of the SENTINEL project.

Work package models

Euro-Calliope is a model based on the Calliope energy modelling framework. Calliope is a framework to build energy system models, designed to analyse systems with arbitrarily high spatial and temporal resolution, with a scale-agnostic mathematical formulation permitting analyses ranging from single urban districts to countries and continents (Pfenninger and Pickering, 2018). Its key features include the ability to handle high spatial and temporal resolution and to easily run on high-performance computing systems. A range of peer-reviewed publications have been based on Calliope models, including to study uncertain demand in district energy systems (Pickering and Choudhary, 2021, 2019); the levelized cost of power-to-methane in Europe (Morgenthaler et al., 2020); the impact of replacing cooking technologies in Italy (Lombardi et al., 2019b); and the optimal spatial allocation of renewable energy in Italy (Lombardi et al., 2020) and Europe, using the Euro-Calliope model (Tröndle, 2020a; Tröndle et al., 2020). The Euro-Calliope model used in this study is based on version 0.6.6 of the Calliope framework. It models the greenfield deployment of components of the energy system at the a sub-national level, in 98 regions across 35 countries in Europe, as a linear programming problem. Its objective function is to minimize total system costs. The model is set up at hourly resolution for a full year, and deploys technologies overnight to fulfil hourly demand in each modelled region.

EnergyPLAN is an energy system analysis developed by the Sustainable Energy Planning Research Group at Aalborg University (Lund and Thellufsen, 2020). It is designed in Delphi Pascal, has a detailed graphical user interface, that allows the user to model and simulate the yearly operation of the entire energy system. EnergyPLAN uses an hourly time resolution to simulate the operation of the electricity, heating, cooling, transport and industry sector. The simulations are conducted deterministically and the same inputs, in the same version, will always generate the same outputs. To conduct the hourly analyses, EnergyPLAN relies on time series data of energy demands and renewable energy profiles. This is combined with annual demands, capacities, costs and efficiencies to determine the energy balance for the given system. EnergyPLAN can operate in technical simulation and market simulation. The technical simulation seeks to identify a low fuel use solution that seek to utilize as much local renewable energy as possible, where the market simulation identifies the lowest marginal cost solution, inspired by the NORDPOOL electricity market. This requires the modelling of an external electricity market. EnergyPLAN currently has over 7,000 users and has been run to carry out a large number of analyses. Most typical are country analyses, such as Denmark (Lund and Mathiesen, 2009) and Ireland (Thellufsen et al., 2019), but EnergyPLAN is also used on cities (Menapace et al., 2020) and regions (Yuan et al., 2020). EnergyPLAN is also used to assess the performance of different technologies for the transition towards renewable energy systems. Examples are smart charge and vehicle to grid in electric vehicles (Lund and Kempton, 2008), power to X solutions (Ridjan et al., 2014) and heat pumps (Lund et al., 2016). Furthermore, EnergyPLAN has initiated work on a number of other tools that utilize its capabilities, such as the EPlanOpt model (Prina et al., 2018). Within the work here, both the latest stable release

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of version 15.1 and the 16.0 beta version will be used. The 16.0 is expected to go as a stable release around summer 2021. Thus, EnergyPLAN 16.0 will be the main tool used for EnergyPLAN modelling in the SENTINEL project.

The Integrated Model to Assess the Global Environment (**IMAGE**) is a comprehensive integrated modelling framework of interacting human and natural systems (Stehfest et al., 2014). The model framework is suited to large scale (mostly global) and long-term (up to the year 2100) assessments of interactions between human development and the natural environment, and integrates a range of sectors, ecosystems, and indicators. IMAGE assesses the impacts of human activities on the natural systems and natural resources, and how such impacts hamper the provision of ecosystem services to sustain human development. The model input consists of socio-economic pathways and projects the implications for energy, land, water, and other natural resources, subject to resource availability and quality. Unintended side effects, such as emissions to air, water, and soil, climatic change, and depletion and degradation of remaining stocks (fossil fuels, forests), are calculated and taken into account in future projections. The IMAGE framework consists of different components: agriculture and land use, energy supply and demand, earth system, impacts and policy responses. The IMAGE Energy Regional model, also referred to as TIMER, is a simulation model and explores the energy system in the broader context of the IMAGE global environmental assessment (van Vuuren, 2007). The results obtained depend on a single set of deterministic algorithms, according to which the system state in any future year is derived entirely from previous system states. It describes 12 primary energy carriers in 26 world regions and is used to analyse long-term trends in energy demand and supply in the context of the sustainable development challenges. The model simulates long-term trends in energy use, issues related to depletion, energy-related greenhouse gas and other air polluting emissions together with land-use demand for energy crops. The focus is on dynamic relationships in the energy system, such as inertia, learning-by-doing in capital stocks, depletion of the resource base, and trade between regions.

Table 1: SENTINEL Work Package 4 model matrix.

	Euro-Calliope	***EnergyPLAN***	***IMAGE***
Input parameters	Energy demand; min/max technology characteristics and capacity limits; node interconnections; investment and operation costs (economic, land use, emissions).	Annual and hourly energy demands & fuel consumption; technology characteristics and capacities; annual district heating production; investment, O&M and fuel costs.	GDP & population; autonomous/price-induced efficiency improvement; activity change (parameters); technological change; available resources & depletion; emission factors
Output parameters	Supply/storage/transmission technology capacities; land use; technology operation; economic costs; CO_2 emissions	Primary energy supply; annual production; economic costs; CO_2 emissions; electricity import-export	GHG emissions; primary, secondary & final energy use; electricity system capacities; land use & land cover; costs; radiative forcing
Spatial scope	Europe (35 countries)	Local/National	Global
Spatial resolution	Sub-national to national (98 regions)	Region represented as single node	26 world regions
Temporal scope	1 year	1 year	1 year
Temporal resolution	1 hr	1 hr	1 year
Supplier assumptions	Capacity as decision variable Operation as decision variables	Capacity as input parameter Operation as decision variables	Capacity as decision variable Operation as decision variables
Consumer assumptions	Exogenous demand per energy carrier	Exogenous demand	Exogenous demand per sector
Decision-maker assumptions	Minimise discounted lifetime economic cost of whole system, while balancing supply & demand in every region	Balance heat & electricity demand, Reduce critical excess electricity production	Based on multinomial logit --> market share of technology depends on relative costs to competing technologies (parameter market sensitivity)
Paradigmatic questions	• What are the trade-offs between geographic scale, cost, and infrastructure requirements for fully renewable electricity supply in Europe? • What supply-side options exist to reduce land requirements of a fully renewable electricity supply in Europe? • How can grid-scale storage impact the cost and operability of national electricity systems?	• How can the European energy systems transition to 100% renewable energy while consuming a sustainable level of bioenergy? • How can cross-sector integration increase renewable energy penetrations? • What role does district heating play in the decarbonization of national energy systems?	• How does the energy system look if the world stays well below 2 °C this century? • What is the emissions gap between current implemented policies and well below 2 °C? • What is the climate change impact on renewable energy production? • Are there alternative pathways for 1.5 °C that limit BECCS? • What are the implications of lifestyle changes?

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Identified user needs and research questions

Through a combination of interviews, surveys, and workshops, key user needs associated with energy models have been identified within the SENTINEL project (Gaschnig et al., 2020). These identified needs include:

1. Modelers should aim at a **holistic and systemic perspective**, taking into account different energy-related sectors where possible.
2. Modelers who seek to be relevant for influential policymakers for the European energy transition should **design their models and case studies to support policy decisions** by assessing policy options and impacts.
3. Modelers should **strive for maximum transparency in order to build confidence and trust in models**.
4. Modelers should **involve stakeholders in their model development and application process**.

Stakeholder involvement in model development was taken further in a series of workshops in November and December 2020. In these workshops, parallel sessions focussed on various facets of SENTINEL energy models in the context of different case studies: Greece, Nordic countries, and Europe. Members of the Euro-Calliope, EnergyPLAN, and IMAGE modelling teams led sessions on transforming the power sector, sector coupling, and decarbonisation of industry, gaining further insight into how best to develop and apply the respective models. Research questions identified prior to the workshops were posed to stakeholders, resulting in a set of the most relevant questions on which to focus model development.

In the context of the identified user needs, we identify three critical model shortcomings:

1. Models fail to represent all technologies which could be critical to the energy transition.
2. Models have not been wholly designed with a focus on assessment of policy options and impacts.
3. Transparency in data inputs and model implementation is lacking in some models.

The models in Work package 4 suffer from these shortcomings to differing degrees, leading to different focusses in model development. Of these shortcomings, Euro-Calliope and EnergyPLAN developments have focussed on the first. This includes electrified heat, mobility, and industry in Euro-Calliope and carnot batteries in EnergyPLAN. IMAGE has focussed on the remaining two, by forming policy-driven scenarios and re-packaging the software modules in an open and transparent manner. The following section will detail the developments undertaken for each model.

Model developments to match user needs

Euro-Calliope

The focus of Euro-Calliope development has been on incorporating all energy-consuming sectors in Europe into a tractable energy system model. The initial model, Euro-Calliope v1.0 (Tröndle, 2020b), focussed only on the power sector and only on current electricity loads. To match user needs, namely in taking a holistic and systematic approach and in being able to address pressing policy decisions, all energy-consuming sectors in Europe have now been incorporated into Euro-Calliope. This section will detail the process of incorporating each of these sectors: household and commercial heat, passenger and freight transport, industry process heat and feedstocks, and all other sectors including agriculture. For each sector, demand and supply technology data has been acquired from various sources and combined in an automated workflow, openly available on GitHub. A data source overview is given in Table 2, for those data accessed for the purpose of adding new sectors. For a detailed understanding of data sources used in Euro-Calliope v1.0, refer to Tröndle et al. (2020).

Building heat sector

Heat demand in buildings has been grouped into three end-uses: **space heat, hot water, and cooking**. These groups match the Eurostat household end-use categorisation, national data for which became available in 2020 (nrg_d_hhq). This data has been used to assign the consumption of fuels to different end-uses. JRC IDEES data has been used to infer building heat demand in the commercial and industry sectors. The consumption of fuels has been further transformed to a demand for heat by assuming technology efficiencies of heating technologies including boilers and direct electric heaters (see Table 2). These efficiencies are consistent with those used in Euro-Calliope for the same technologies. Heat pumps are a special case, since heat demand can be calculated using the consumption of ambient heat: demand = ambient heat consumption + electricity consumption. Annual water and space heat demands are used to scale hourly demand profiles produced using the methods implemented for the When2Heat database (Ruhnau et al., 2019), updated to account for (a) all Euro-Calliope countries and (b) the sub-national distribution of single- to multi-family homes across Europe, according to the Eurostat database of dwellings. Cooking heat demand profiles are generated using a bottom-up stochastic modelling. The approach extends the open-source RAMP engine (Lombardi et al., 2019a), developed and validated in previous work (Lombardi et al., 2019b) with application to Italy, to stochastically model demand in all European countries.

Table 2: Primary data sources used in Euro-Calliope model development. Resolution is given in the context of the Nomenclature of Territorial Units for Statistics (NUTS). Eurostat dataset codes are given in parentheses.

Source name	***Data accessed***	***Resolution***	***Use of data***	***Sectors affected***
Eurostat	Annual energy balances (*nrg_bal_c*)	NUTS0	Energy data in all subsectors	All
	Annual household energy end-uses (*nrg_d_hhq*)	NUTS0	Household end-use energy consumption	Household heat and electricity
	freight loading (*road_go_na_rl3g*)	NUTS3	Sub-regional disaggregation of industry demand	Industry
	employees by subsector (*sbs_r_nuts06_r2*)	NUTS2		
	dwelling number and types (*cens_11dwob_r3*)	NUTS3	Heat demand generation	Building space and water heat
	Gross value added by commercial subsector (*nama_10r_3gva*)	NUTS3	Sub-national disaggregation of commercial demand	Commercial building and transport
Joint Research Centre (JRC)	JRC IDEES (Mantzos et al., 2017)	NUTS0	Attribution of consumed resources per subsector to end-uses	All
	JRC open power plant database (Kanellopoulos K. et al., 2019)	Site-specific	Location of existing conventional power supply technologies	Power
Swiss federal office for energy (SFOE)	Swiss equivalent of Eurostat data	NUTS0	Energy data in all subsectors, sub-regional demand disaggregation	All
Danish energy agency	Technology catalogue	N/A	Technology costs and operational characteristics	Heat, electricity, and renewable fuels

Table 3: Heat technology efficiencies used to translate consumed energy resources into demand for end-use heat.

	Technology	***Efficiency***
Space and water heating	Gas (natural gas, biogas)	0.97 (The Danish Energy Agency, 2019)
	Petroleum products	0.9 (The Danish Energy Agency, 2019)
	Solid fossil fuels	0.8 (assumed the same as for solid biofuels)
	Solid biofuels	0.8 (Chandrasekaran et al., 2013; Mermoud et al., 2015; The Danish Energy Agency, 2019)
	Solar thermal	1.0 (as per Eurostat energy balance methodology)
	Direct electric	1.0
Cooking	Gas (natural gas, biogas)	0.28 (Karunanithy and Shafer, 2016)
	Petroleum products	0.28 (assume same as gas)
	Solid fossil fuels	0.15 (Ramanathan and Ganesh, 1994) scaled using (Karunanithy and Shafer, 2016)
	Solid biofuels	0.1 (Ramanathan and Ganesh, 1994) scaled using (Karunanithy and Shafer, 2016)
	Direct electric	0.5 (Karunanithy and Shafer, 2016)

To meet these demands, a range of new technologies are defined in the model, key data for which can be found in Table 3. We source most data for these from the Danish Energy Agency Technology Catalogue (The Danish Energy Agency and Energinet, 2016). Heat pumps are a special case, since their performance is based more strongly on weather conditions. Our heat pump coefficients of performance (COPs) are based on a catalogue of 78 heat pumps provided by the manufacturer WAMAK. The WAMAK heat pump performance data represents state-of-the art technology and generally fits that given by previous studies (Figure 1) (Nouvel et al., 2015; Ruhnau et al., 2019; Staffell et al., 2012). Following Ruhnau et al. (2019), we assume COP to be 80% of published performance. The WAMAK catalogue data also includes actual technology heat delivery capacity, relative to nominal capacity (Figure 2). That is, the nominal capacity in which one invests is not the actual capacity that is realised, which instead depends on sink and source temperatures. We describe heat pumps using hourly COP and capacity variation; both timeseries rely on hourly temperature data from the MERRA-2 reanalysis (Gelaro et al., 2017)[1].

Table 4: Key data for heat supply technologies in Euro-Calliope. Data is almost exclusively 2050 estimates from the Danish Energy Agency technology catalogue (2016). Greater detail can be found in the model implementation.

Technology	***Energy input***	***Efficiency***	***Capital cost (EUR2015/kW)***
methane boiler	Methane	97%	172
biofuel boiler	Biofuel	80%	445
air source heat pump	Electricity	Time varying COP	662
ground source heat pump	Electricity	Time varying COP	1100
solar thermal panels	Solar irradiance	Time varying efficiency	515
direct electric heaters	Electricity	100%	695
Combined heat and power plants	Waste / biofuel / methane	Depending on heat to power ratio	520 - 2783
hot water storage	Heat	0.01-0.02%/hour	3 (large-scale) – 410 (small-scale) EUR2015/kWh

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[1] Air-source heat pumps use surface air temperature while ground-source heat pumps use sub-surface temperature (*tsoil5*) – 5°C, to account for heat transfer to the ground loop brine

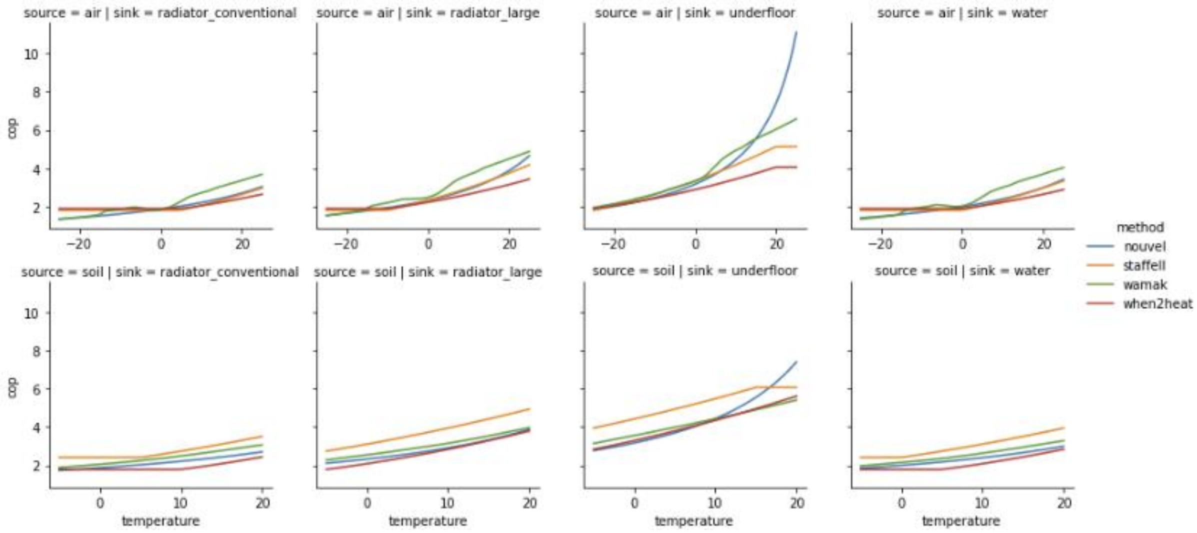

Figure 1: Comparison of heat pump coefficients of performance for different source and sink temperatures, as well as different technology types (air-source and ground-source heat pumps). Methods are named based on first authors of the respective studies (Nouvel et al., 2015; Ruhnau et al., 2019; Staffell et al., 2012), except WAMAK which is the manufacturer name from which performances were extracted from a catalogue of technologies.

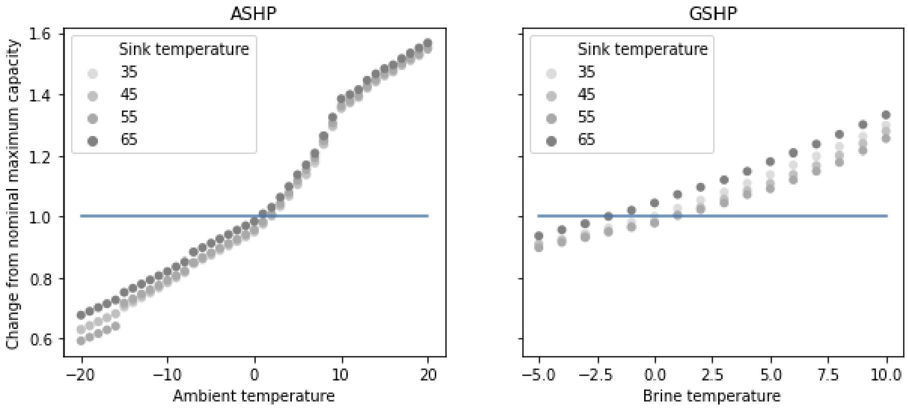

Figure 2: Change in heat pump delivery capacity as a function of source and sink temperature, based on the average performance of several heat pumps in the WAMAK catalogue of technologies.

Transport sector

The transport sector encompasses road, rail, air, and shipping. Electrification is only possible in some of these forms of transport, namely road and rail. In rail, complete electrification is assumed possible, such that all current fuel oil demand is replaced by direct electricity demand in 2050. The current consumption of fuel is taken from Eurostat, while the efficiency of different rail drive trains is taken from JRC IDEES. For air and shipping, the opposite is assumed: there will be no electrification by 2050. Instead, the kerosene and diesel demand of these two forms of transport must be met by synthetic fuel generation. Accordingly, air and shipping (domestic and international) demands are taken directly from Eurostat. Unlike the other modes, we do not assume a 'winning' drive train for road transport. Instead, we calculate the distance travelled by all vehicles in each country and use this distance as the demand in the model. Annual vehicle mileage is based on JRC IDEES and is split into motorcycles, passenger cars, busses, light-duty commercial vehicles, and heavy-duty freight vehicles. Vehicle mileage is then transformed back to energy demand based on the efficiency of different drivetrains. The energy consumption per unit distance data given in Table 5 are based on the 25th percentile of all countries' vehicle energy consumption, as given by JRC IDEES for the year 2015. This represents a convergence on higher efficiency of vehicles in all countries in Europe, but not an improvement in countries with existing efficient vehicle fleets.

Only light-duty electric vehicle and passenger rail demands are assumed to have hourly profiles impacting energy delivery; all other demands must be met on an annual basis, since they are synthetic fuels. Rail electricity profiles are taken from the DESTINEE demand model (Boßmann and Staffell, 2015). Electric vehicles are limited in the allowed energy delivery per hour based on the number of vehicles connected to the grid at any given time. We generate this plug-in profile using RAMP-Mobility, an extension of the aforementioned open-source RAMP engine (Lombardi et al., 2019a). The result is that in some hours, as few as 70% of electric vehicles are plugged in (Figure 3). The available charge capacity of plugged-in vehicles is based on the number of vehicles and an average battery size (The European Council for Automotive R&D, 2019). The result of this is that if the model chooses to electrify half a region's vehicle fleet of 100 cars, then there will be a maximum of 50 cars plugged in, each with a battery of 0.08MWh. Thus, 4MWh of energy can be delivered to vehicles in that hour. This method allows the model to decide when to charge cars (smart charging), but ensures that it is not unrealistic in the frequency of charging throughout the year (i.e. it cannot choose to charge all vehicles in one week of the year). However, initial tests showed that this was still not sufficient to ensure "realistic" EV charging, with regions having little to no EV charging in January weeks (Figure 4). Accordingly, a bound on EV supply was applied using weekly EV electricity demand from RAMP-mobility (Figure 3).

*Table 5: Euro-Calliope average vehicle fleet energy consumption by drivetrain (oil or electricity driven) and battery capacity of electric vehicles. Vehicle classes and energy consumption values are based on JRC IDEES; energy consumption is the 25th percentile of energy consumption across all JRC IDEES countries in 2015. Battery capacity is an average of values given by The European Council for Automotive R&D (EUCAR) (2019). *these values are not given by EUCAR, so are assumed.*

Vehicle class	***Energy consumption (MWh/million km)***		***Battery capacity (MWh)***
	Oil	*Electricity*	
Heavy duty vehicle	5140	N/A	0.2
Light duty vehicle	855	480	0.1*
Motorcycle	419	200	0.01*
Bus	6057	3248	0.2*
Passenger car	675	324	0.08

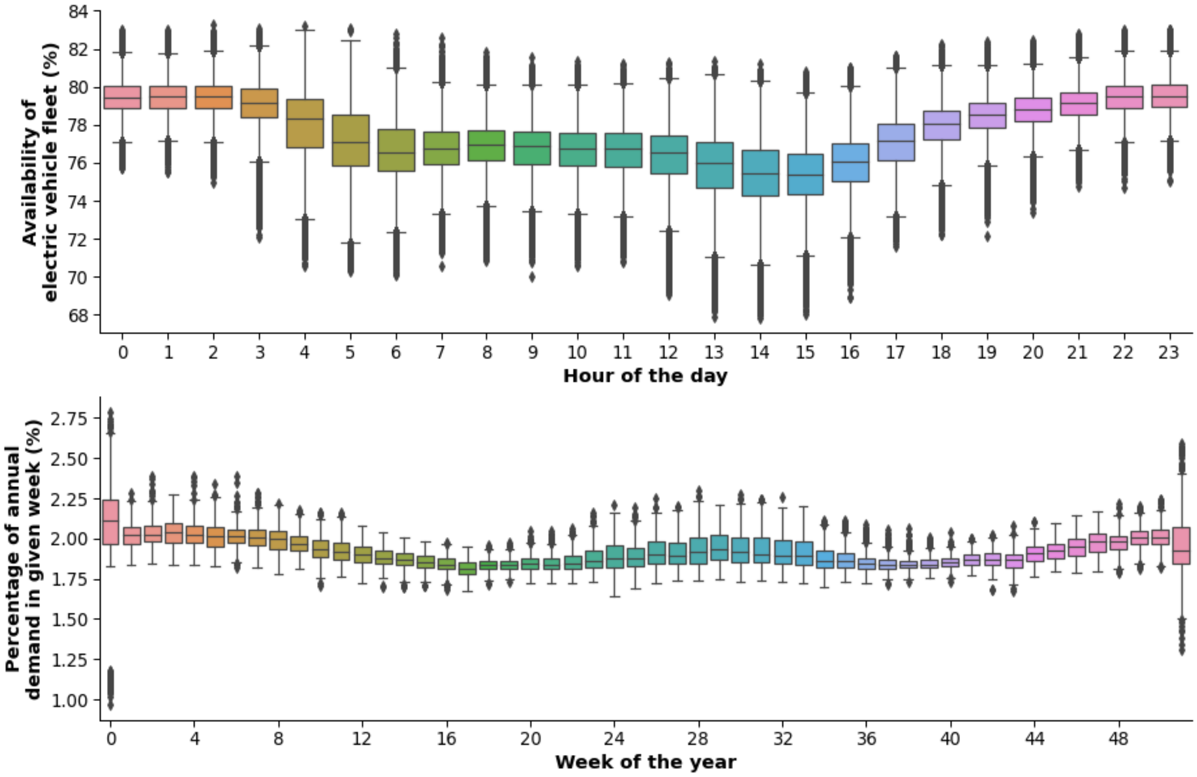

Figure 3: Overview of Euro-Calliope electric vehicle hourly plug-in schedule (top) and weekly demand (bottom), based on national stochastic profiles modelled in RAMP-mobility. Boxplots show the variation in availability per hour of the day (top) and week of the year (bottom), across years 2000. Top: All hours are given in UTC+00:00, not local time. Bottom: Increased range of outliers in weeks 0 and 52 are due to short weeks at the start and end of the time period.

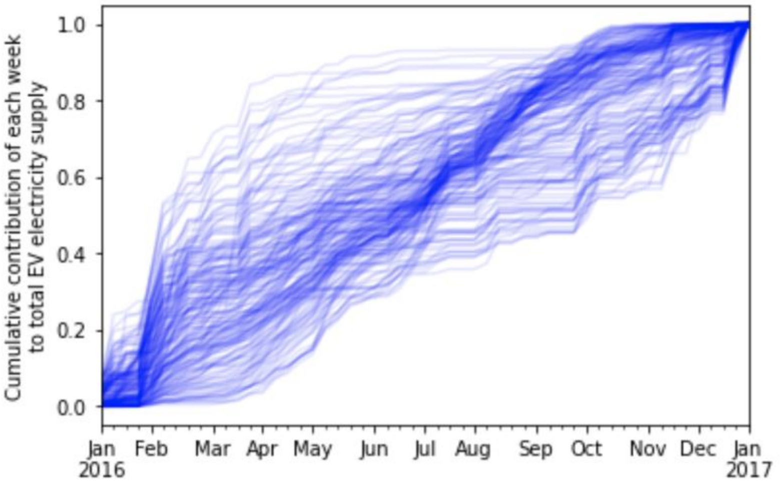

Figure 4: Normalised cumulative weekly EV charging across a year, based on results from optimising cost in the Euro-Calliope model. Lines represent all 98 Euro-Calliope model regions and both electrified heavy-duty and light-duty vehicles. Each line has a low opacity, so high opacity areas indicate a greater degree of overlap.

Industry sector

The industry sector has demand for different levels of heat (space heating, low temperature heat, and high temperature heat), for already electrified or electrifiable end-uses (namely, operation of machinery), and for consumption of energy resources as feedstock (such as oil for the production of base chemicals). There are no European statistics on the breakdown of fuel consumption that can be attributed to each end use, but some countries publish their own statistics. Countries with sufficiently disaggregated demand data are Germany, Austria, and the UK. Switzerland also has disaggregated data, for *either* the fuel consumption per industry subsector or the end use demand of industry in total, but not the fuel consumption per end use per industry subsector.

Both bottom-up and top-down approaches to understanding industrial energy demand have been undertaken to date (Fleiter et al., 2017; Mantzos et al., 2017; Naegler et al., 2015; Rehfeldt et al., 2018; Reiter et al., 2016). Top-down modelling attempts have mapped the end use demand of industry subsectors from a subset of contexts to all countries in Europe; for instance, Naegler et al. (2015) use the German industry data in their analysis. Mantzos et al. (2017) also undertake a top-down analysis to create the JRC-IDEES database, although it is unclear whether any country-specific end-use data was used to inform their model. Bottom-up modelling has used the FORECAST-Industry demand modelling tool (Fleiter et al., 2017; Rehfeldt et al., 2018; Reiter et al., 2016), which demands a level of data input that is beyond the scope of our study. The HeatRoadmap Europe project (Fleiter et al., 2017) is an extension of Rehfeldt et al. (2018), with the focus on a different reference year (Fleiter et al.: 2015, Rehfeldt et al.: 2012). There is no ground truth for industry end use demand, and datasets rarely align. Therefore we utilise the JRC-IDEES database, given that its structure best matches the data on total sectoral energy consumption published by Eurostat, as well as the use of 13 subsectors. JRC-IDEES provides sufficient data to understand electrified and electrifiable processes, as well as high and low temperature processes. We assume that steam processes still require methane[2], while all other processes can be electrified, according to the efficiencies provided in JRC-IDEES. A remaining issue is the consumption of fossil fuels as feedstock to industrial processes. Such consumption contributes to a large proportion of emissions in the chemicals industry (Madeddu et al., 2020) as well as for iron production (Suopajärvi et al., 2018). To mitigate these emissions, new methods or feedstocks are required in the chemicals and steel industries, as will be detailed in the remainder of this subsection.

Iron and Steel

The process for producing steel requires two key steps: 1. iron ore to iron, and 2. iron to steel. In its current form, the first step is almost entirely conducted using *Blast Furnaces* (BFs) to

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[2] Moving forward, and following from the work of Madeddu et al. (2020), we will likely also look to electrify high temperature steam processes.

produce "pig" iron (high carbon content iron) which cannot be fully decarbonised without CO2 capture, due to the reliance on unreplaceable coke as the iron ore reductant (Mandova et al., 2018; Material Economics, 2019). A small (~6%) quantity of iron is produced as *Direct Reduced Iron* (DRI) (Word Steel Association, 2019), which relies on hydrogen (via natural gas) instead of carbon to reduce the iron ore. Although a proven process, the cost of reducing agent prohibits its large scale deployment (Material Economics, 2019).

The second step is currently dominated by the use of a *Basic Oxygen Furnace* (BOF), which reduces the carbon content of pig iron, to produce steel. The BOF requires large amounts of heat, as well as a source of oxygen (usually air), and is hard-linked to the BF as one unit, the *Blast/Basic Oxygen Furnace* (BF-BOF). This route releases CO2 in the combustion of fuels, the production of lime and coke, and in the removal of oxygen from iron ore and excess carbon from pig iron, to produce steel (Suopajärvi et al., 2018).

The steel sector is highly circular, already around 85% of produced steel is recycled and approximately 40% of steel produced in Europe is from scrap (Material Economics, 2019). Scrap steel enters the BF-BOF route, with blast furnace heat used to melt the scrap for addition into the basic oxygen furnace alongside iron, at about 10-20% of input ferrous material (Suopajärvi et al., 2018). The remaining (majority of) scrap is processed using *Electric Arc Furnaces* (EAFs), which is an entirely electrifiable route of melting and recasting steel that accounted for 29% of all crude steel production in 2018 (Word Steel Association, 2019).

Without carbon capture, the current BF-BOF cannot be fully decarbonised; only parts of the process could be replaced with biomass-based alternatives (Mandova et al., 2018; Material Economics, 2019; Mathieson et al., 2011; Suopajärvi et al., 2018, 2017). However, the direct reduced iron route could be decarbonised by direct use of hydrogen, instead of extracting it from natural gas. This process, known as H-DRI, could produce iron with low to no emissions. Following this, the electric arc furnace could be used as the primary method to produce steel; scrap steel and iron would be combined with a splash of carbon from coal to produce crude steel (Material Economics, 2019). A study as part of the Hybrit project found that the H-DRI-EAF route would emit approximately 97% less CO2 than the BF-BOF route, for the same crude steel production (Vogl et al., 2018). A less well developed, but potentially more energy efficient route for iron production involves direct electrolysis of iron ore (electrowinning). This technology is still at the laboratory phase (Fischedick et al., 2014), so little is known about its energy consumption at an industrial scale[3]. Indeed, it is explicitly not considered in the scenarios presented by the Material Economics consortium (2019).

In Euro-Calliope, we consider H-DRI-EAF as the primary route for future, decarbonised steel production, with an expected increased use of recycled steel overall to 50% of total ferrous material input (see Figure 5). This is in line with the Material Economics "new processes" pathway. Unlike these pathways, but similar to Hybrit, we would not only consider biomass sources of hydrogen, but also (and primarily) production by electrolysis from excess

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[3] Fischedick et al. (2014) use 9.3GJ/t crude steel in their calculations.

renewable generation. The hydrogen requirement for H-DRI is approximately 51kg per tonne of steel output (Vogl et al., 2018), not accounting for the use of scrap steel in the EAF. That is, if 50% of the ferrous input in the EAF is scrap steel, and 50% is iron from H-DRI, then 25kg of Hydrogen would be required. In addition, electricity is needed for both the H-DRI and EAF processes. The Hybrit pre-feasibility study gives 2,633 kWh electricity for Hydrogen production, 322kWh for H-DRI, and 494kWh for EAF (+380kWh biomass and 42kWh coal), all per tonne of crude steel. Vogl et al. (2018) agree on the electrolyser electricity consumption, but give 753kWh_e/t for EAF, approximately 250kWh/t for heating of iron ore, and <50kWh/t for H-DRI. Both ultimately give approximately 3,450kWh_e/t for the whole process, if no scrap steel is used, which is similar to the 3,640kWh_e/t given by Fischedick et al. (2014). On top of this, iron ore pelletising/sintering and downstream steel casting/rolling require 833 and 28/805 kWh, respectively (Worrell et al., 2007).

Assuming 50% scrap and the production of one tonne of liquid steel, consumption of energy becomes: 25kg H2, 135kWh_{th} for iron ore heating and use in the H-DRI process, 710kWh_e/t for EAF, and 111kWh_e+625kWh_{th} for pelletising, sintering and continuous casting[4]. Additionally, the "sponge" iron (output from H-DRI) can be allowed to cool and stored, effectively providing a buffer between energy production for H-DRI and for EAF; however, 159kWh/t is then required to reheat the iron for use in EAF. We ignore the requirement for coal and lime in the steel-making process but include energy demand for product 'finishing', as given by JRC-IDEES (Mantzos et al., 2017), which comes in at around 60-70kWh_{th}/t.

Quantity of steel production

For each country, the quantity of produced steel is required to understand future energy demand. Very few countries publish this data as part of Eurostat's PRODCOM database, so we instead use data on annual production for a select number of countries (Word Steel Association, 2019) to verify that energy consumption for iron and steel correlates with annual production, then map that to all Euro-Calliope countries.

All European countries (not including Turkey, Ukraine, Russia, and other CIS members) produced 172.8Mt of crude steel in 2018, 100Mt of which was produced by the BF-BOF route and the remaining 72.8Mt by EAF. BF-BOF derived steel is well matched to blast furnace energy consumption given by Eurostat (99.3% Pearson correlation; Figure 6a). All steel industry energy consumption is marginally less well matched to all crude steel production (97% Pearson correlation; Figure 6b**Error! Reference source not found.**), but still offers a useful avenue to disaggregate European steel production. In 2050, it is predicted that steel production will have increased across Europe to 199Mt[5]. This value is disaggregated to countries using total iron and steel subsector energy consumption.

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[4] We take the lower bound energy consumption for casting/rolling (i.e. for casting) since continuously cast steel makes up 97% of total crude steel production in the EU (Word Steel Association, 2019).

[5] 193Mt from EU (Material Economics, 2019) + 6Mt from rest of Europe, using the same methodology of a 15% increase in steel production from 2016 to 2040.

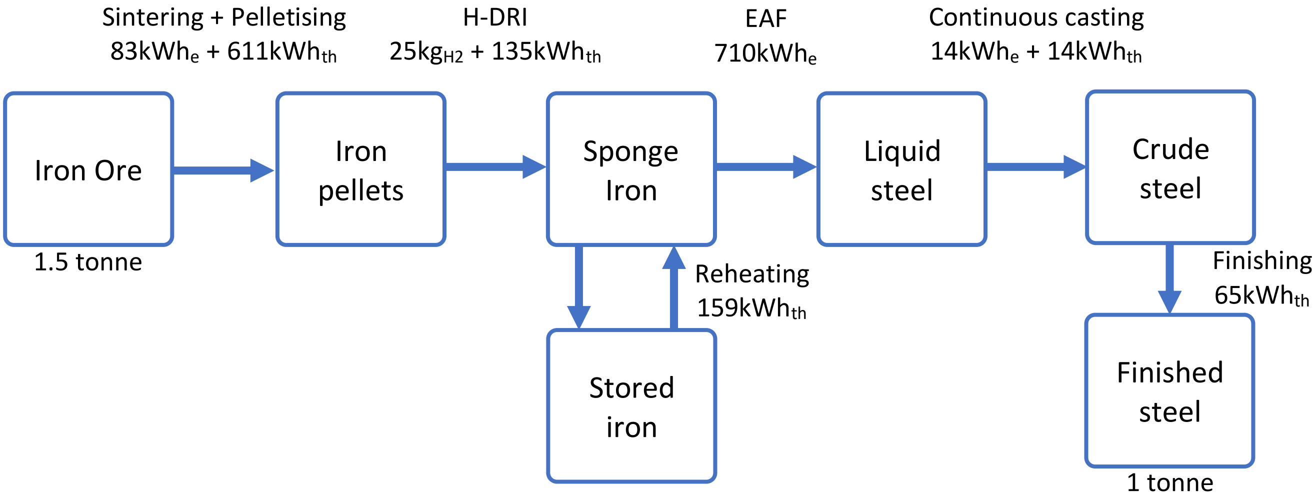

Figure 5: Iron -> Steel processes and the energy requirements to produce one tonne of cast steel

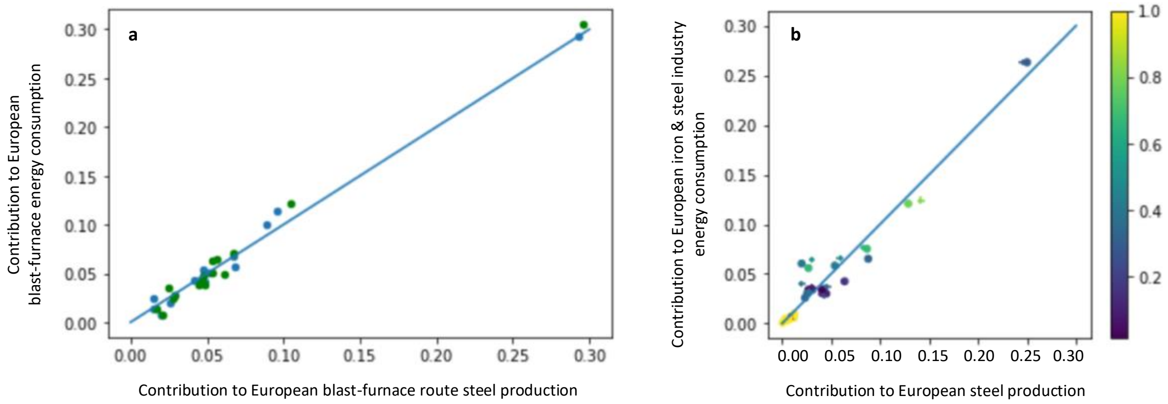

Figure 6: (a) Contribution of each European nation to total European BF-BOF steel production compared to national contribution to European blast furnace energy consumption. Blue = 2015, Green = 2018. (b) Contribution of each European nation to total European steel production compared to national contribution to European iron and steel industry energy consumption. Circles = 2015, crosses = 2018; colormap gives relative contribution of EAF to total steel production in each country. In both subplots, line shows correlation=1.

Chemicals

The chemical and petrochemical industry covers the production of end-use plastics, fertilizers, pharmaceuticals, and many other chemicals (glues, cleaning fluid, etc.). Of these, it is petrochemicals that require fossil feedstock; ammonia (for fertilisers), high value chemicals (HVCs, for plastic production), and methanol (for plastics and other chemicals) account for 90% of fossil feedstock in the chemical industry (International Energy Agency, 2018).

Plastics

There is a wide variety of plastics, almost all of which originate from the "cracking" of naphtha or liquified petroleum gas (LPG) into "high value chemicals" (HVCs) such as ethylene, propylene and BTX (benzene, toluene and mixed xylenes). The route to generating HVC without fossil fuel cracking is via methanol (Bazzanella and Ausfelder, 2017), which can be synthesised by hydrogenation of CO2 or gasification/pyrolysis of biomass or waste plastics. Methanol synthesis is essentially the same as production of synthetic natural gas or synthetic liquid fuels, just with different compositions of the input gases. The energy requirements of these routes are given in Bazzanella and Ausfelder (2017) and are (sometimes loosely) used by Material Economics (2019) in its pathway generation. The "new processes" pathway assumes that chemical plastic recycling (40%) and biomass-to-plastics (33%) will dominate plastic generation in 2050, along with mechanical recycling (13%) and improved circular economies (14%). **Error! Reference source not found.** gives the process chains to realise final plastics production, with the inclusion of the option of hydrogen to plastics (Bazzanella and Ausfelder, 2017). Energy requirements in some processes are ignored in Material Economics (2019), and indeed there is little information available on some processes, including chemical recycling. Nevertheless, it is understood that external energy sources will be required to maintain e.g. the 900C required in a gasifier (Saebea et al., 2020). An additional route, mechanical recycling, could require 7MWh/t HVC (Bazzanella and Ausfelder, 2017), but this magnitude is too high relative to the available data on chemical recycling. Indeed, from various Swedish sources, Liljenström and Finnveden (2015) found mechanical recycling to have an average energy consumption of 0.37MWh/t HVC. A summary of these pathways is given in Figure 7.

According to the Material Economics "new processes" pathway, 28.8Mt of plastics in Europe will be generated by chemical recycling, 23.8Mt by new production (biomass or hydrogen), and 9.36Mt by mechanical recycling; an additional 10.1Mt would be circulated internally, so we do not consider them as energy consuming. This contrasts with the 64Mt of production in 2016 (60Mt by conventional means) given by Material Economics and Plastics Europe (2019), and 47Mt of HVCs currently produced in Europe, according to the International Energy Agency (2018). The discrepancy between HVCs and plastics probably stems from imports of HVCs as well as production from other base chemicals.

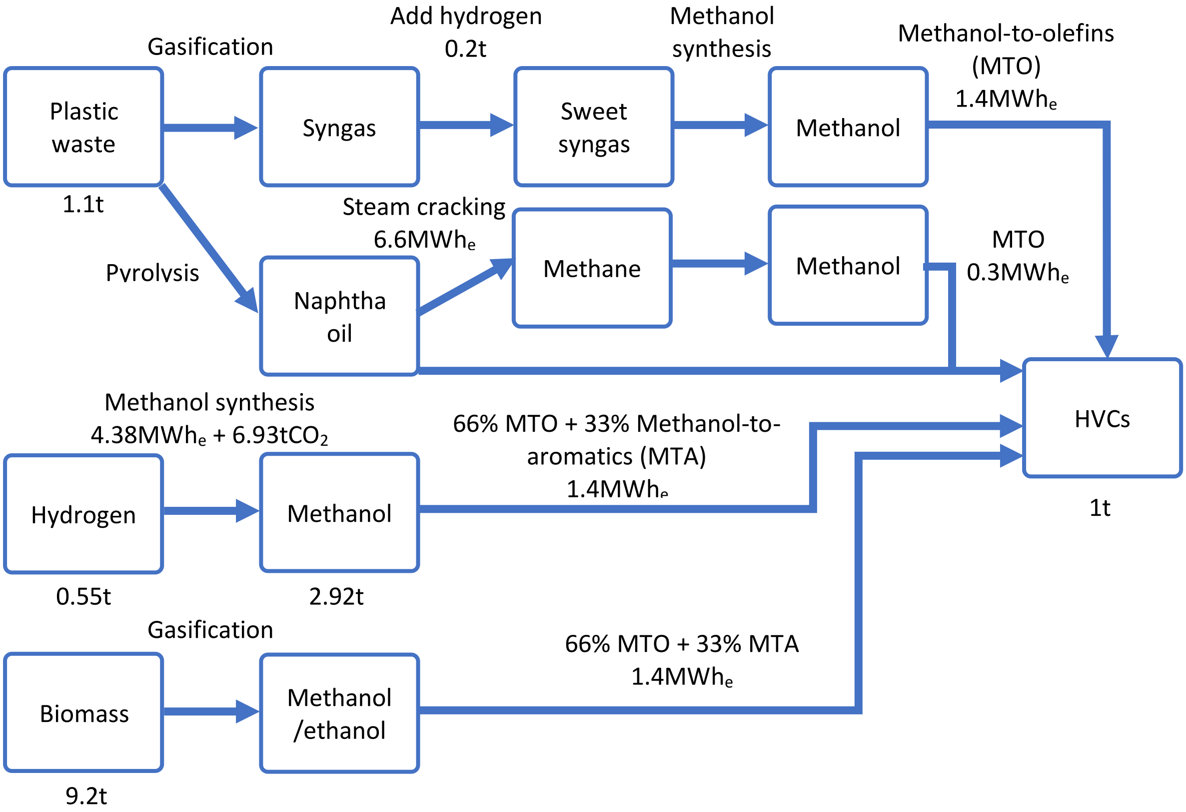

Figure 7: Possible routes to zero/low carbon plastic production, based on a combination of Material Economics (2019) and Bazzanellla et al. (2017). There are some data gaps with no reliable source, including energy demand for plastic gasification and pyrolysis. Biomass gasification energy use is incorporated into its overall efficieny (hence the high input requirements).

Some countries have a greater discrepancy than others in their production of HVCs and subsequent production of end-use plastics. The Netherlands consumes 4.3% of Europe's converter plastics (penultimate step before reaching end-use plastics) (AISBL, 2019) but produces 18% of EU-28's ethylene+propylene (see PRODCOM database), while Germany both produces 24.6% of those two chemicals and consumes 24.6% of Europe's converter plastics. Since we are concerned with replacing fossil feedstocks, we will focus on the generation of HVCs, and therefore use non-energy consumption of Naphtha from the Eurostat annual energy balances to infer national contributions to European production of HVCs. Figure 8 shows that this is a reasonable assumption, with Naphtha consumption more often matching PRODCOM data compared to plastics production data. This comparison comes with the caveat that many countries have no PRODCOM data, and BTX HVCs are not included (again, for lack of PRODCOM data).

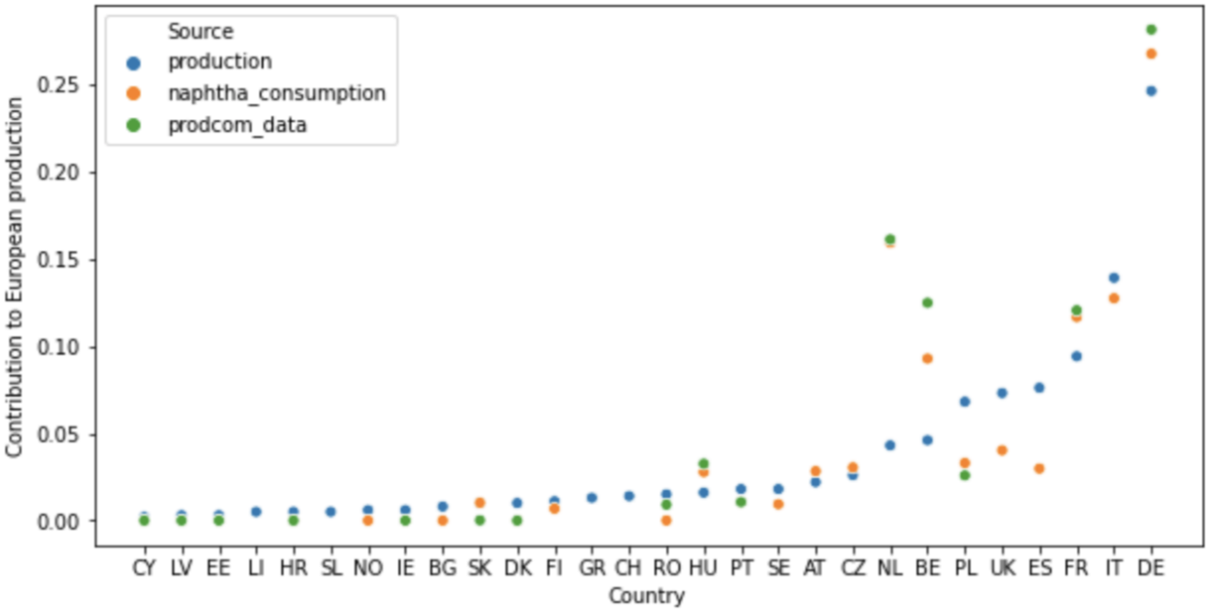

Figure 8: Comparison of data sources to infer the contribution of countries to European HVC production in 2018. 'production' is the contribution to production of end-use plastics according to Plastics Europe (AISBL, 2019), Naphtha consumption is from Eurostat energy balances, and 'prodcom_data' relates to published data on produced volume of Ethylene and Propylene, where available.

Ammonia and Methanol

Produced from steam reformation of natural gas or gasification of coal, ammonia and methanol rely on a source of hydrogen for their production. Ammonia is produced by combination of hydrogen and nitrogen, while methanol is produced by the combination of hydrogen and CO2. Of the replacement fossil feedstocks, this is the most straightforward: Ammonia requires $0.178t_{H2}/t$ + $1.73MWh_{e}/t$ for compression and N_2 production; Methanol requires (as seen in the previous subsection) $0.189t_{H2}/t + 1.5MWh_{e}/t + 1.373t_{CO2}/t$ (Bazzanella and Ausfelder, 2017). An additional component of this process chain is urea, which currently relies on the steam and CO_2 output of Ammonia production, adding $0.92MWh/t + 0.32_{tCO2}/t$ urea. Table 6 shows the annual production of Ammonia, which ranges from 15 to 28Mt in a year. Given the collection of values in the range 15-19 Mt, we take 17Mt as the annual production, as given by Bazzanella and Ausfelder (2017), based on a dataset from Fertilizers Europe which is no longer available. We also take the urea production from the same source: 6Mt, leaving 13.6Mt for direct ammonia and 3.4Mt for ammonia-> urea[6].

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[6] 0.57 tonnes ammonia is needed per tonne of urea (Bazzanella and Ausfelder, 2017).

Table 6: Annual ammonia production in Europe (EU or all Euro-Calliope regions) according to various sources.

Source	***Year***	***Quantity***
International energy agency (2018)[7]	N/A	27.5Mt ammonia
PRODCOM	2017	16 Mt ammonia (13.1 Mt N)
USGS[8]	2017	18 Mt ammonia (14.6 Mt N)
Boulamanti and Moya (2017)	2013	19 Mt ammonia
Fertilizers Europe	2017	15 Mt ammonia (12.4 Mt N)
Bazzanella and Ausfelder (2017)[4]	2016?	17 Mt ammonia

Bazzanella and Ausfelder (2017) depend on PRODCOM for methanol production data, which was 1.6Mt in 2018. This compares to 4.5 Mt given by the International energy agency (2018). Global demand for Methanol was 75 Mt in 2015, 3% of which was produced in the EU (International Energy Agency, 2018), giving 2.6 Mt. Based on these fluctuating values, we take a value of 2 Mt.

Molar contributions

To match with JRC IDEES basic chemicals (given in weight of ethylene), we take their values of production and attribute them by molar ratio to plastics, ammonia, and methanol. Results of this are shown in Table 7. Applying this to the JRC IDEES dataset leads to an overprediction of chemical production (by about 10-15%); this is expected, since we do not cover all basic chemicals in this analysis.

Table 7: Comparison of basic petrochemicals, including their approximate annual production in Europe, molar mass, and molar contribution to total moles of basic chemicals produced.

Chemical	***Annual production (Mt)***	***Molar mass***	***% molar share of chemicals***
Ethylene	21.7	28.05	32.1
Propylene	17.0	42.08	16.8
BTX	15.7	93.00[9]	7.01
Ammonia	17.0	17.01	41.5
Methanol	2.00	32.04	2.59

In Euro-Calliope, we consider chemical production as requiring a combination of three molecules: CO2, H2, and methanol. Together, these can be used to produce the basic chemicals for plastics, as well as ammonia and urea. We estimate the quantity of each basic

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[7] Base source is Fertilizers Europe, but data nitrate subsets (e.g.., ammonia) is only available to paying members.

[8] Only covers 22 of the Euro-Calliope countries (probably the biggest producers). Alternatively, taking total global production of 144Mt multiplied by the 9 and 12% contribution of the EU, according to fertilizers Europe and the IEA, respectively, we get 12.9-17.3Mt.

[9] Average of the components of BTX, which range from 78 to 106 g/mol.

This project has received funding from the *European Union's Horizon 2020 research and innovation programme* under grant agreement No *837089*.

chemical produced in Europe, and assume that each country produces the same relative share of those chemicals. With this assumption, we can disaggregate the JRC IDEES estimate of national production of basic chemicals (in kt ethylene) to the chemicals of interest, and from there calculate the demand for CO2, H2, and methanol based on data of each transformation technology (Bazzanella and Ausfelder, 2017). This gives the annual demand for CO2 (kt), H2 (MWh LHV), and methanol (MWh LHV) for the chemical industry of each country.

Other industry subsectors

Feedstocks are not such a concern in other industry subsectors, so JRC IDEES data can be used directly. The only changes envisioned in these subsectors is the electrification of machinery and medium temperature processes. The only subsector which produces notable emissions through processes that cannot be decarbonised is the cement industry. There is speculation about the possible avenues for processes and materials that could be used to mitigate cement industry emissions (Madeddu et al., 2020; Material Economics, 2019), but these are rarely energy-based solutions. Therefore, we ignore non-energy emissions from the cement industry.

Other sectors

The final sectors not covered by any of the previous subsections are agriculture & forestry, fishing, and "not elsewhere specified". These sectors account for approximately 2.5% of total European annual energy demand. According to Eurostat, "not elsewhere specified" demand is attributed to the military, among other things. These sectors are not handled completely by JRC IDEES, so a different method has been employed. All oil consumption is assumed to be for mobility and added to annual demand for heavy-duty vehicles (*agriculture & forestry* and non-kerosene use in *not elsewhere specified*), shipping (*fishing*), and aviation (kerosene in *not elsewhere specified*). All other non-electricity consumption is assumed to be for heating applications, and therefore added to annual commercial heat consumption.

Synthetic fuel production

All subsectors have the option, or indeed the requirement, to meet demand with net-zero emission hydrocarbons (henceforth 'synthetic fuels'). Kerosene, diesel (used also as a proxy for petrol), methanol, and methane are energy carriers in Euro-Calliope. All of these fuels can be generated from electricity or biofuels. If generated from electricity, then hydrogen and CO_2 are first produced from electrolysis and direct air capture, respectively, before being combined in various processes to produce the hydrocarbons. These processes and associated technologies have been primarily collated from the Danish energy agency technology database (The Danish Energy Agency, 2019); direct air capture data is taken from Fasihi et al. (2019) and electrolysis data matches that used by Francesco et al. (2020).

Euro-Calliope regionalisation

To represent the geographic disparity across all energy-consuming sectors, a sub-national spatial resolution was deemed necessary. However, two issues arise when moving to a subnational level: (1) administrative regions are often not at the correct resolution or are at significantly different resolutions between two countries[10], and (2) the transmission system is not well understood by modellers below the national level. Between countries, Net Transfer Capacities (NTCs) are available from European Network of Transmission System Operators for Electricity (ENTSOE). At a sub-national level, this is rarely the case. To address both these issues we adopt a regionalisation first developed within the European Commission Seventh Framework Programme project e-HIGHWAY 2050. Within this project, a pan-European transmission system representation was developed based on grouping NUTS3 administrative regions to 106 model regions (Anderski et al., 2014). Grid transfer capacities between model regions were calculated in e-HIGHWAY 2050 based on a detailed, proprietary understanding of the transmission system. By assuming the same model regions, we are able to ensure a high resolution as well as a detailed understanding of transfer capacities of the transmission system in Euro-Calliope. Figure 9 shows the final 98 Euro-Calliope model regions[11], including all possible inter-region transmission connections. These connections include those already existing in e-HIGHWAY 2050 as well as planned connections in the medium and long term, predominantly high voltage DC (HVDC), according to ENTSOE 2018 network development plan (TYNDP). The inclusion of all planned HVDC lines matches the expectation voiced by stakeholders in the SENTINEL European case study workshop that HVDC will play an ever more important role up to 2030 and beyond. We use known costs or expected costs of TYNDP planned connections to estimate transmission expansion costs in Euro-Calliope, grouping transmission lines into five types based on technology and geographic context (Figure 10). Each line type cost spans a relatively large range; we take the median cost for the baseline Euro-Calliope model in each instance.

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[10] For instance, Germany has 401 NUTS3 regions, while France has 101; France has almost twice the land area, and 80% the population of Germany, but has ¼ the number of NUTS3 regions.

[11] There are 98 model regions in Euro-Calliope compared to 106 in the original e-HIGHWAY 2050 model due to not including neighbouring countries (including Russia, Belarus, Ukraine, and Northern African countries).

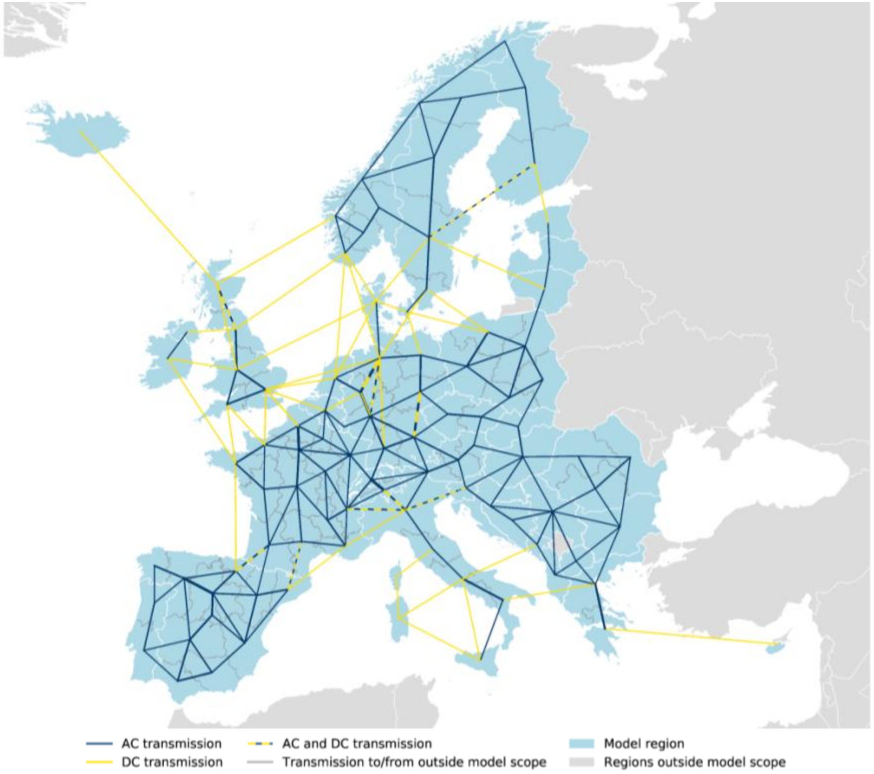

Figure 9: Euro-Calliope 98 regions and inter-regional transmission lines. Lines are coloured based on the type of transmission available between regions. Thicker transmission lines represent larger minimum grid transfer capacities.

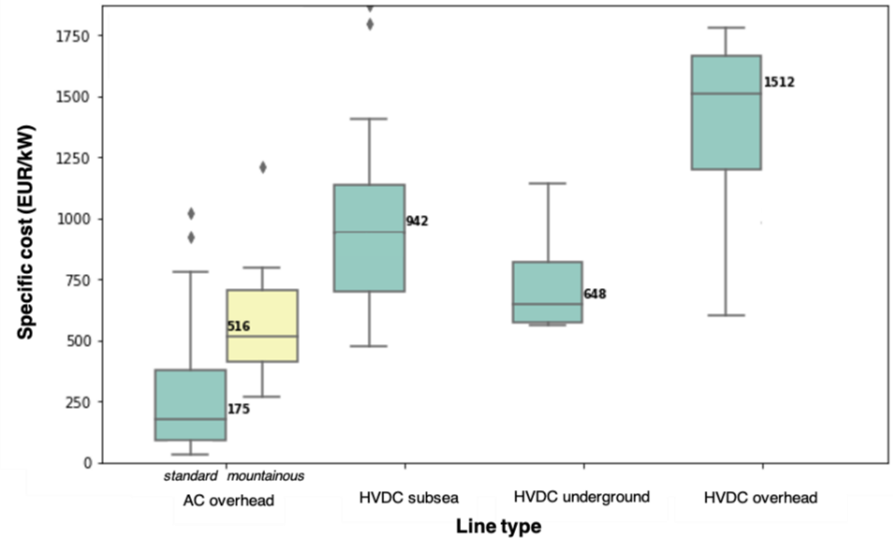

Figure 10: Distributions of transmission costs for five line types. AC = Alternating current, HVDC = high voltage direct current. AC lines are split into those which span mountainous regions and those that do not. Distributions are based on costs of implementing recent line extension projects as well as budgets for planned extensions; there are 92 data points in total.

To regionalise sub-sectors, different datasets have been used for different end-uses. In each case, several sub-national indicators were compared to samples of published regional data, to test their viability. **Household and public and private passenger transport demand is regionalised using population**[12]. **Commercial building and light-duty vehicle demand is regionalised using NUTS3 Gross Value Added** (GVA) from non-industrial subsectors (classifications *G-U*). **Industry demand, including from freight transport, is regionalised depending on subsector**. For industries with emitters registered in the EU-ETS, the location and size of emitters in 2014 have been used for regionalisation (Figure 11). We found that these largest emitters capture most subsector emitters in each country, when compared to Eurostat annual emissions balances within each subsector (Figure 12). For all other subsectors, the number of employed individuals in each industry sub-sector (NUTS2) was found to be the best indicator, but did not provide sufficient resolution for full disaggregation. NUTS3 regionalisation is therefore achieved by combining number of employees with the quantity of loaded freight in each industry subsector. **Demand for aviation and shipping fuels is disaggregated based on average industry regionalisation**, on the assumption that these fuels would be synthetically generated in industrial regions, rather than exclusively at the point of consumption (e.g. major ports for shipping fuel). Grouped, annual regionalised demand is given in Figure 13. Hotspots for each end-use clearly differ, with northern Italy, the Netherlands, south-east UK, and western Germany showing most prominently. The benefit of regionalisation is clear from this figure. Figure 13b shows the extent of the challenge to full European decarbonisation that sector-coupling could have. Once all non-transport sectors are considered, energy demand increases by a factor of three in winter and 2.5 in summer. In addition, the hourly variability of demand is exacerbated by heat demand in winter. Both magnitude and variability will be further increased by road transport. It is crucial to understand how this increased magnitude and variability can be met by a fully renewable energy system.

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[12] In the UK context, we found that subnational gas and electricity demand (Department for Business, Energy & Industrial Strategy, 2019) was best correlated with population. Other indicators we tested include built environment land-use, GDP, and heating degree days.

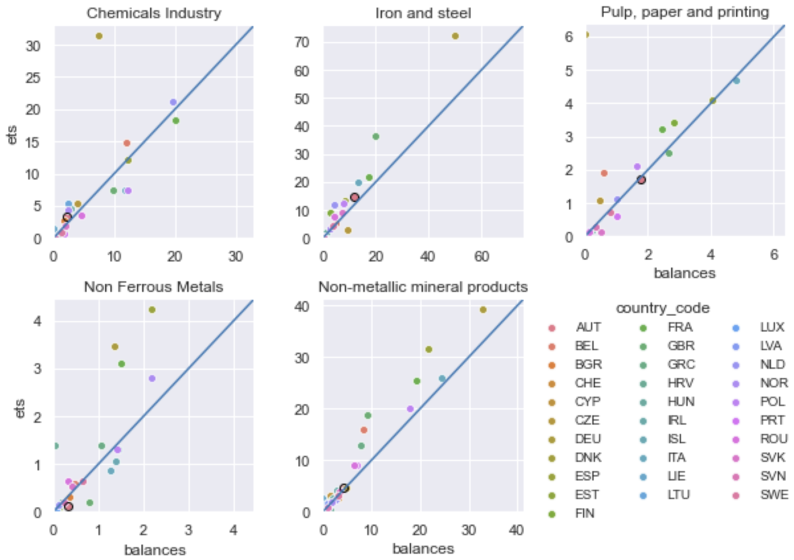


Figure 11: Spatial distribution of all sites which report to the EU-ETS / ERPTR and whose data has been collected in the Hotmaps database (3411 sites) as well as a further scraping of the EU-ETS database (722 additional sites). Marker colour depicts subsector classification, while the marker size relates to quantity of actual emissions reported for the year 2014.

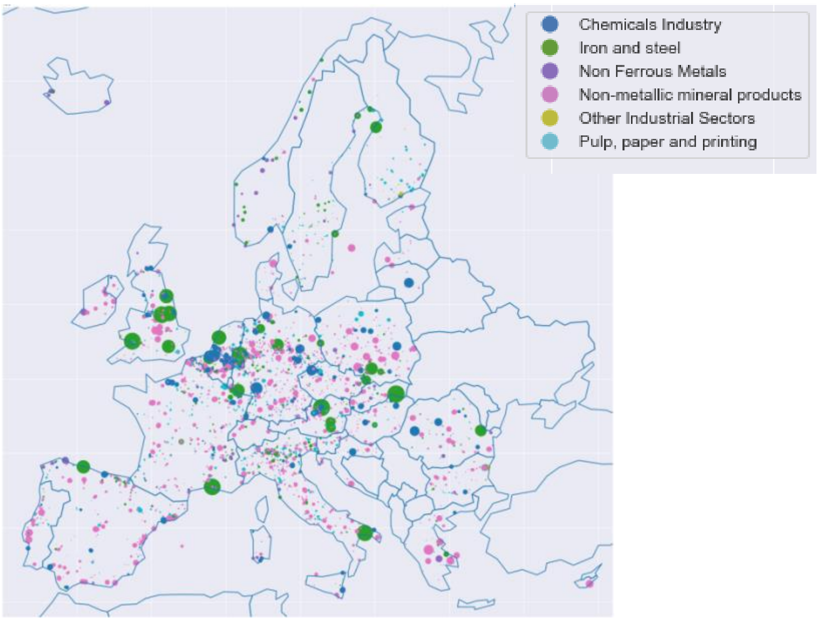


Figure 12: Published industry subsector emissions ("balances") compared to the sum of reported emissions from industry sites within each subsector, via the EU-ETS ("ets"). Austria is highlighted by a black marker edge. Extreme outliers are caused by reporting inconsistencies; e.g. Chemicals industry emissions in Germany are not reported in Eurostat under the subsector emissions, but instead grouped into 'Other industry emissions'.

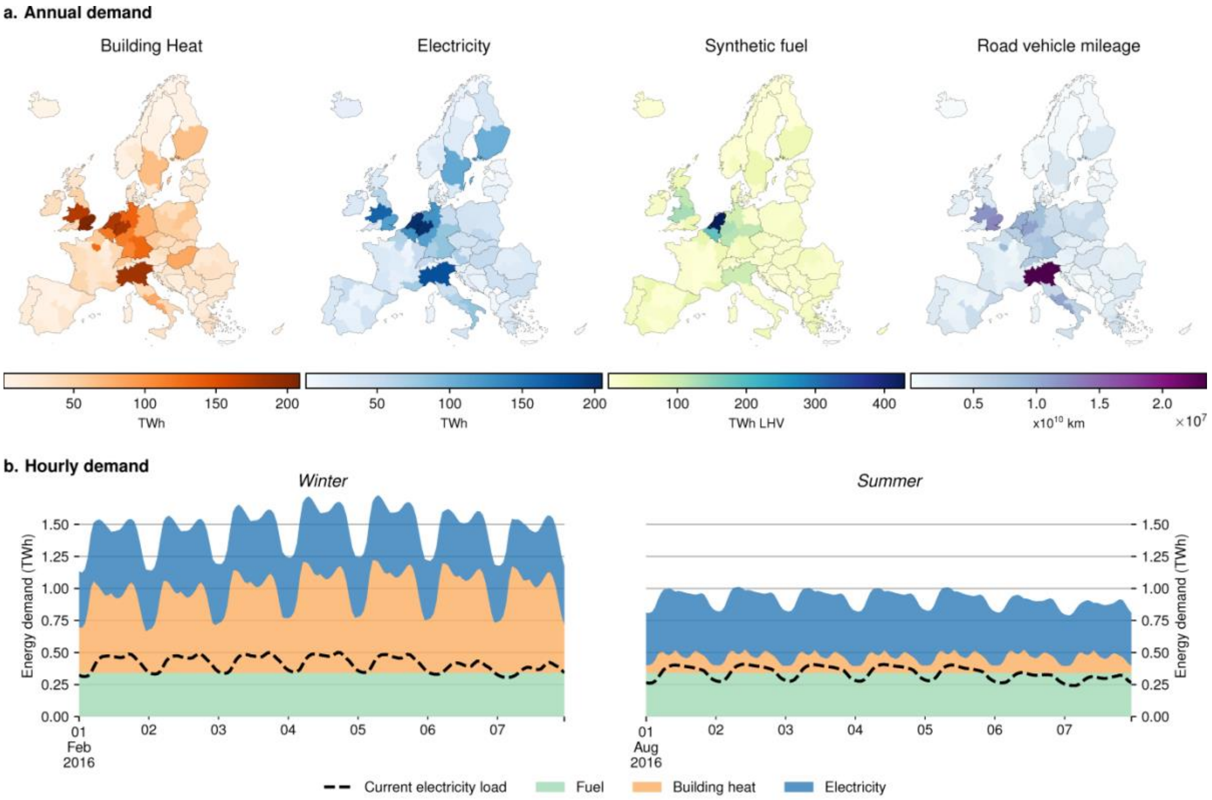


Figure 13: (a) Average (2000-2018) annual cross-sectoral demand per Euro-Calliope region. "Building heat" refers to space heat, hot water and cooking demand. "Electricity" refers to all direct electrical end-use demand. "Synthetic fuel" refers to demand from industry for fuels as feedstock (methanol for Chemicals), high temperature heat, and for aviation and shipping. Demand for Hydrogen and CO_2 is assumed to be directly electrified and thus combined into "Electricity" demand. Road vehicle mileage encompasses all road vehicles; rail has been assumed to be fully electrified and is combined into "Electricity". (b) Example timeseries of energy demand for a winter and summer week, using 2016 data. Groupings are the same as given in (a), with synthetic fuel demand assumed to be constant in every hour. "Current electricity load" refers to 2016 electricity load across all Euro-Calliope countries, according to OPSD data.

Power sector updates

Although the primary aim of Euro-Calliope v2.0 was to add all non-electricity energy sectors to the existing model, some updates were also made to the v1.0 power system model. As well as the aforementioned updates to the transmission system representation, we have included 2050 nuclear power and combined cycle gas turbine (CCGT) technologies, current underground gas storage capacity, and updates to hydropower capacity. Nuclear capacity in 2050 (Table 8) is based on published data of expected capacity in select countries, regionally distributed by current capacity, derived from the JRC open power plants database (Kanellopoulos K. et al., 2019). CCGTs are expected to consume synthetic methane and they have no constraints on total capacity. The cost of CCGTs in 2050 is taken to be the 2040 projection from the UK Department for Business, Energy & Industrial Strategy report on electricity generation costs. Euro-Calliope already relies on Hydropower capacity was already reliant on the JRC Hydro-power database, which we update to version 7 (Matteo De Felice and Konstantinos Kavvadias, 2020). We also remove a scaling step, such that JRC data on pumped storage is used directly, rather than being scaled to fit capacities assumed by Geth et al. (2015).

Table 8: Range of installed nuclear capacity in 2050 for subset of European countries in which some nuclear capacity is planned or under consideration.

	Country	*BGR*	*CZE*	*FIN*	*FRA*	*GBR*	*HUN*	*ROU*	*SVK*
Installed capacity (MW)	*Min*	0	6230	0	22000	8900	2400	650	940
	Max	3200	7860	2750	58600	8900	2400	2650	3340

Filling data gaps

During data processing there are many cases where there are gaps for certain countries, years, end-uses, or energy carriers. Specific data filling can be found in the data processing workflow. The primary data filling methods utilized are:

1. If not available in Eurostat or JRC IDEES, namely Switzerland, nationally published data has been used.
2. Where possible, gaps are filled using total sectoral energy demand. In years with data, an average contribution of each end use to total demand is calculated (e.g. X% of demand is for cooking); this average contribution is then applied to gaps (e.g. cooking demand in year Y = household demand in year Y * X%).
3. If end-use data is unavailable (e.g., for commercial and industrial heat demand), gaps are filled in at the energy consumption stage. The average relative contribution of each energy carrier to each end use is applied to all years without JRC-IDEES data but with Eurostat annual energy balance data.
4. If no data is available from the Eurostat annual energy balances, we take demand to be the average demand for that end-use for all years that we have data.
5. If no data is available at all for a country (e.g., we do not have cooking profiles for some eastern European countries), the average of data from the closest available neighbouring countries is used.

Final sector-coupled energy system model

The final model demands are summarised in Figure 13. In each of the aforementioned sectors, there exists some degree of electricity demand in today's energy system. The extent of this demand is quite limited in some sectors, e.g., 1.7 TWh in 2018 passenger road transport, but can be considerable in others, e.g., 670 TWh in 2018 building heat demand. To avoid double-counting demand, we remove existing heat and vehicle electricity end-use consumption from the electricity load curve.

This project has received funding from the *European Union's Horizon 2020 research and innovation programme* under grant agreement No *837089*.

Finally, although all abovementioned subsectors and energy carriers can be modelled in the Euro-Calliope sector-coupled model, we have made some simplifications in the context of SENTINEL research questions to ensure model tractability:

1. Road vehicles are grouped into *heavy* (heavy-duty vehicles and busses) and *light* (light-duty vehicles, motorcycles, and passenger cars), with electric vehicle plug-in profiles only applied to *light* vehicles.
2. Air-source and ground-source heat pumps are represented by a single technology, whose characteristics are a weighted average of the two main heat pump classes. The weighting is based on the ratio of air- to ground-source heat pump sales in 2016 and 2018, according to the European heat pump association.
3. The number of combined heat and power technologies has been reduced from six to three, by selecting only those technologies that are likely to be more prevalent in future according to expert opinion.
4. Industry feedstock demand for hydrogen and CO2 can only be met by electrification in the model (electrolysis and direct air capture, respectively). We have therefore added this to industry electricity demand directly.

The final flow of energy carriers from supply to demand defined in Euro-Calliope is depicted in Figure 14.

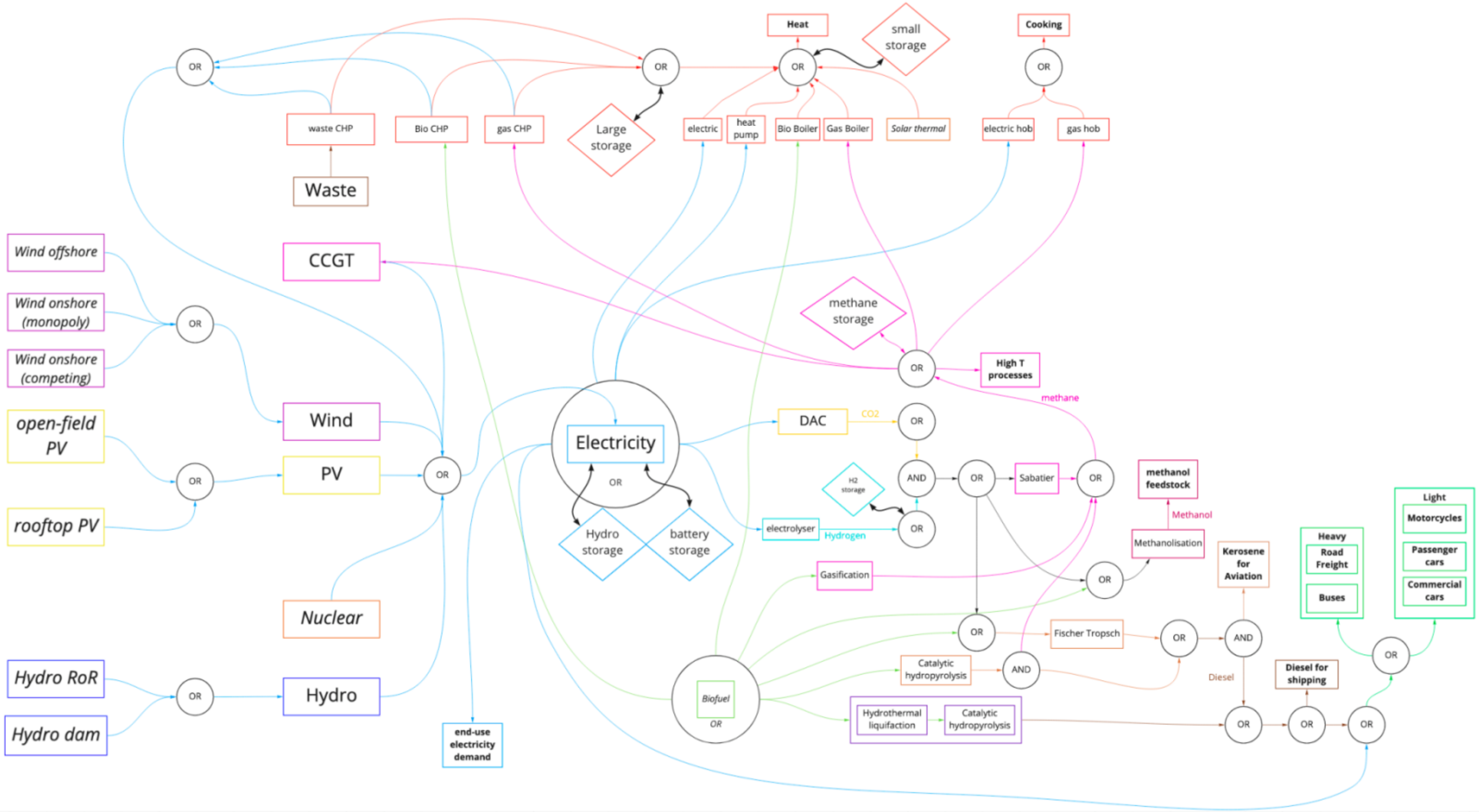


Figure 14: Flow chart of the final Euro-Calliope sector-coupled model, including supply technologies, energy carriers, and demand sources. AND and OR icons in the flow indicate when an in/output is a combination (AND) or choice (OR) of out/input. Where energy enters the systems from an external resource, the carrier is given in italics (e.g. Waste). Storage technologies are depicted as diamonds. Bold text refers to demands, where energy exits the system. Flow line colours are related to the energy carrier flowing along that line.

This project has received funding from the *European Union's Horizon 2020 research and innovation programme* under grant agreement No *837089*.

Updates to the Calliope modelling framework

To represent all new sectors in Euro-Calliope, additional mathematical constraints have been added to the underlying Calliope modelling framework. New constraints include:

- Time varying technology capacity applied to heat pump heat capacity and electric vehicle charging capacity.
- Annual average capacity factor upper and lower bounds applied to nuclear technologies.
- Combined heat and power operating ranges, to capitalise on characteristics provided by the Danish Energy Agency technology database (C_b and C_v coefficients).
- Fixed demand share as a decision variable, applied to the share of heat and transport supply technologies. With this constraint we are able to model the operation of disaggregated technologies, e.g., household heat supply. For instance, if 50% of households invest in heat pumps then only approximately 50% of heat demand can be met by heat pumps in each hour.
- Demands can be time independent. This allows e.g., kerosene for aviation to be generated according to any profile, provided there is sufficient kerosene generated by the end of the model period.

The Calliope framework has also undergone various internal efficiency improvements to reduce pre-processing time and optimisation model size. These improvements were rarely required prior to this modelling effort, since existing models have been sufficiently small to not notice the time and memory penalties. Improvements include:

1. Timestamps are represented by strings in the Pyomo model, not Pandas Timestamps.
2. Constraints in which an upper bound will be set to infinity are not generated, since they already imply that there is no constraint.
3. Timeseries data is handled more frequently using multi-dimensional array operations rather than looping.

EnergyPLAN

During task 4.2, a number of developments have been implemented in EnergyPLAN. These are all based on user needs. The needs are determined through the workshops organized within the SENTINEL project and concrete requests we have received from our daily users of the EnergyPLAN model. Some of the developments are in terms of algorithm and calculation efficiency, some concern specific outputs, some concern new technologies and some concern improved options for external linkages.

Improved options for external linkages

EnergyPLAN can be called externally from another program or by using the command line feature. Here a new updated procedure has been included. This is called "spool" function. This allows for much faster operation of high number of scenarios. This is suited for optimization problems.

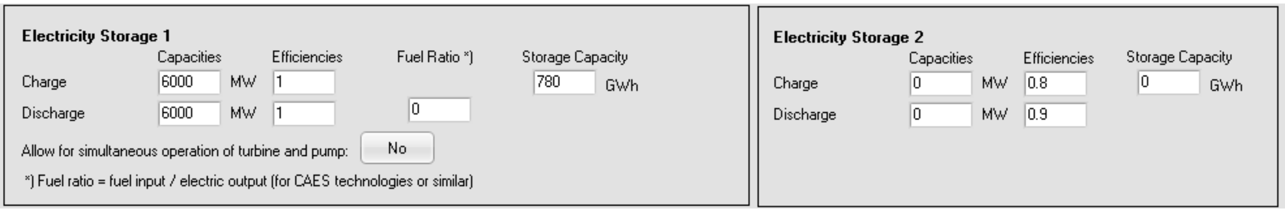
The spool function works in the following manner:

1. The user creates a *spool* sub-directory in their main EnergyPLAN directory, and a *results* subdirectory within the *spool* sub-directory.
2. The user runs a one-line function in the command line of the form: *"EnergyPLAN file path" –spool "number of files" "name of file 1" "name of file 2" "name of file …." –ascii run*
   Example: **C:\ZipEnergyPLAN\energyPLAN.exe -spool 3 basis.txt basis-ny.txt klimakomissionen2010.txt -ascii run**

By including the argument **-spoolhoff**, hourly values can be disabled to maintain smaller output files.

Update to electricity storages

To improve on the energy storage functionality, EnergyPLAN now has the feature of modelling multiple types of electricity storage (Figure 15). First, the user can now model two electricity storages. This includes the ability to both include for instance a pumped hydro and a battery storage facility.



Electricity Storage 1

	Capacities		Efficiencies	Fuel Ratio *)	Storage Capacity	
Charge	6000	MW	1		780	GWh
Discharge	6000	MW	1	0		

Allow for simultaneous operation of turbine and pump: No

*) Fuel ratio = fuel input / electric output (for CAES technologies or similar)

Electricity Storage 2

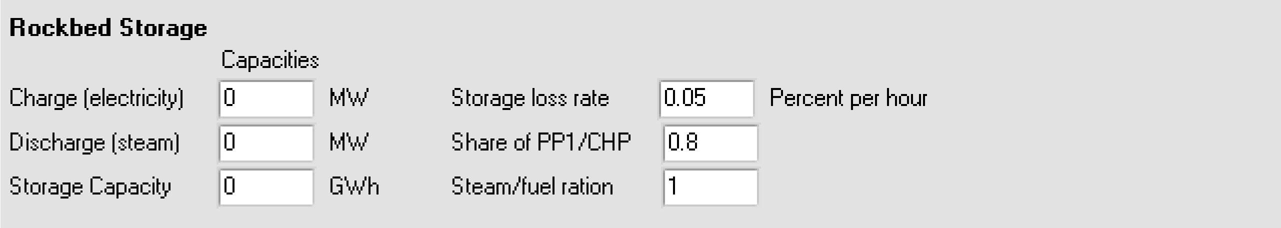
	Capacities		Efficiencies	Storage Capacity	
Charge	0	MW	0.8	0	GWh
Discharge	0	MW	0.9		

Figure 15: View of EnergyPLAN GUI in which two independent energy storage devices can now be defined.

The storages can in principle be any storage technology where the input is electricity and the output is electricity. Currently in both technical and market operation they work based on the merit order that electricity storage 1 will be activated first, followed by electricity storage 2. Potentially a market strategy can be imposed to allow for some differences.

The storages are used, in hours with excess electricity (or low prices), and stored for as long as needed until a situation occurs with either power plant or import situations occurring (high electricity prices in the market operation strategy).

Another electricity storage included now is the rockbed storage/carnot battery (Figure 16). This allows for storing electricity as steam, which in this case can be used as input in steam turbines. Thus, lowering the demand for burning fuels for steam turbines. This feature has the unique capability of being linked to the already existing power plants and combined heat and power plants. Concretely it will store steam in hours with excess renewable energy. The steam is then stored until a situation occurs where the steam can replace a fossil fuel in a power plant. How much fuel the steam can replace and how many plants that has access to the storage can be determined by the user.



Rockbed Storage

	Capacities				
Charge (electricity)	0	MW	Storage loss rate	0.05	Percent per hour
Discharge (steam)	0	MW	Share of PP1/CHP	0.8	
Storage Capacity	0	GWh	Steam/fuel ration	1	

Figure 16: View of EnergyPLAN GUI in which a rockbed storage/carnot battery can be defined.

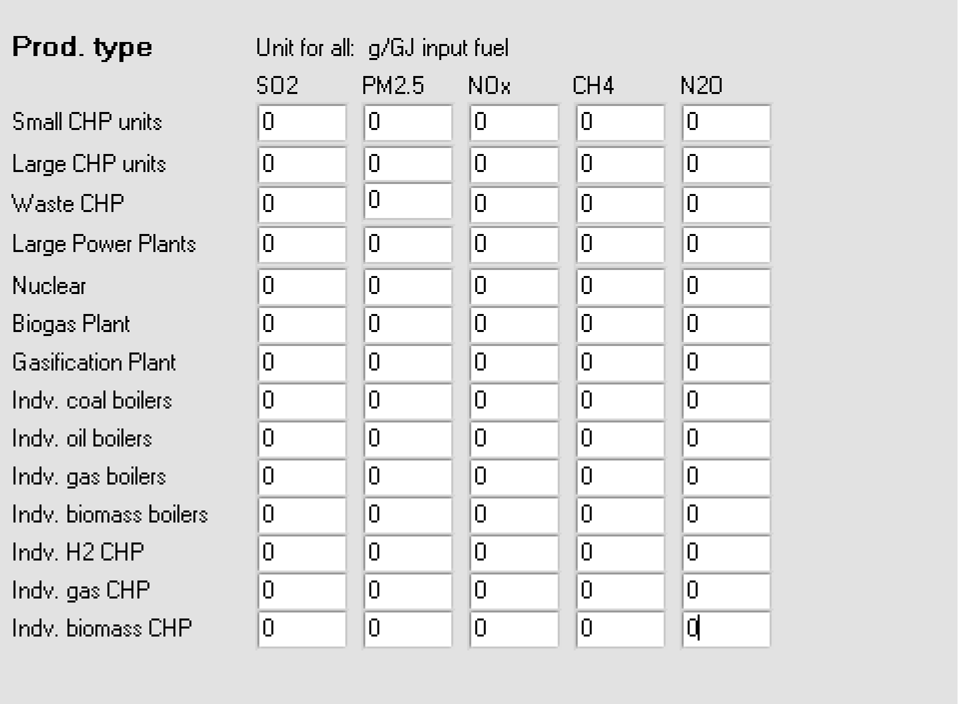
More detailed emission accounting

Based on discussions with users, the need to assess environmental impacts beyond CO_2 emissions was highlighted. While EnergyPLAN cannot include a detailed economic impact assessment/life cycle perspective, it is possible to detail emissions from combustion processes. Thus, a new *emissions* tab has been added to the EnergyPLAN interface.

EnergyPLAN can already calculate CO_2 emissions, by multiplying an emissions factor for each fuel type with the amount of fuel combusted. The extent of other emissions is more technology specific. Thus, a new module has been added where the user can specify an emission factor for each technology that can be included in the energy system (Figure 17). Specifically, the following emissions can be investigated:

- NO_x
- SO_2
- CH_4
- $PM_{2.5}$
- N_2O

The inclusion of these additional indicators allows the user to conduct more detailed climate impact assessments (CH_4 and N_2O), as well as to analyse air pollution and local environmental impacts ($PM_{2.5}$, NO_x and SO_2). The emissions associated with a model instance are summarized in EnergyPLAN alongside all other existing outputs.



Prod. type Unit for all: g/GJ input fuel

Prod. type	S02	PM2.5	NOx	CH4	N20
Small CHP units	0	0	0	0	0
Large CHP units	0	0	0	0	0
Waste CHP	0	0	0	0	0
Large Power Plants	0	0	0	0	0
Nuclear	0	0	0	0	0
Biogas Plant	0	0	0	0	0
Gasification Plant	0	0	0	0	0
Indv. coal boilers	0	0	0	0	0
Indv. oil boilers	0	0	0	0	0
Indv. gas boilers	0	0	0	0	0
Indv. biomass boilers	0	0	0	0	0
Indv. H2 CHP	0	0	0	0	0
Indv. gas CHP	0	0	0	0	0
Indv. biomass CHP	0	0	0	0	0

Figure 17: View of technology emissions input table in the EnergyPLAN user interface.

Re-structured output file format

To increase the interpretability of EnergyPLAN results, a new output data structure is undergoing development. This new data structure will present results in a machine-readable tabular format, with multiple pre-set aggregation levels. This new 'tidy' data structure will facilitate ease of use when conducting studies that require quick manipulation of multiple scenario output files. Likewise, this facilitates the process of coordinating linkages with other tools and applications, with clearer defined semantics of the outputs generated by EnergyPLAN.

Increased accessibility of EnergyPLAN

To increase the accessibility of EnergyPLAN, current and past versions of the documentation are now stored on the Zenodo repository. The documentation is therefore easier to refer to, and versioning is more transparent. Furthermore, an EnergyPLAN methodology paper is in the process of being published, which will enable a stable reference point for all published research which rely on the tool.

IMAGE

The IMAGE model has been modified to improve the representation of EU modelling, and a pilot project was started to comply with the 'open source' feature of the SENTINEL project.

The IMAGE model is an integrated assessment model to analyse global change for a set of global environmental issues and sustainability issues, such as climate change (Stehfest et al., 2014). It consists of a land use model, energy model (TIMER), and global vegetation model, including carbon and water fluxes (LPJmL), impacts model, and policy response model (FAIR). The IMAGE Energy Regional (TIMER) model is a recursive-dynamic model; thus, the decisions are being taken based on existing information without foresight. It projects global and regional energy supply and demand for the industry, transport, residential, services and other sectors.

Open-source pilot

One of the main objectives of the SENTINEL project is to ensure the transparency of the models and to make them freely and openly available on the online platform. The current IMAGE model is programmed in the MyM language (Beusen et al., 2011) where the user needs to specify a (time-dependent) mathematical model. However, MyM is not commonly used in research, is not publicly available, and is strictly limited to representation of mathematical equations which has its drawbacks. Therefore, we started a pilot project to transfer one module of the TIMER model to Python, which is the fastest growing language at the moment (Srinath, 2017). This will enable us to cooperate more with other models and use and share code. Much attention has been paid to the structure of the model and the use of classes supported by the object-oriented features of Python (see Section **Error! Reference source not found.**). In addition, coding guidelines were developed in line with PEP8 style guide for python code to enable multiple people to work together on model development. The new coding uses 'numpy arrays' and other convenient data types for more self-explanatory coding and newly unlocked possibilities. Finally, much attention is given to structure the code to improve efficiency of memory and runtime.

Residential Energy Model-Global

Three sub-modules of the original REMG (Residential Energy Model-Global) (Daioglou et al., 2012) have been translated from MyM to Python, and the project will continue during 2021. These residential sector modules are the Building Stock, Insulation, and Appliances sub-modules. The model is publicly available on GitHub:

https://github.com/imagepbl/Residential-Sector-IMAGE-TIMER-

The Buildings Stock module (Figure 18) has a dynamic and explicit description of the building stock enabling a detailed estimation of key indicators such as, residential energy demand and emissions. The main input to the module are exogenously developed floorspace projections that assume a causal relationship with household expenditures, and calibrated with census data. The floorspace simulates the yearly inflows and outflows of the global building stock from 1971 to 2100, distinguishing per region, income class, and age. The Building Stock module includes a decomposition of the stock into new buildings, decommissioned buildings (buildings that are near the end of their lifetime and are demolished and reconstructed), and abandoned buildings (those are similar to decommissioned buildings, but they are not reconstructed). By tracking the building stock, a bottom-up and consistent calculation of buildings' envelope efficiency across building vintages can be done. This in term allows for determining the heating and cooling energy demand for different vintages.

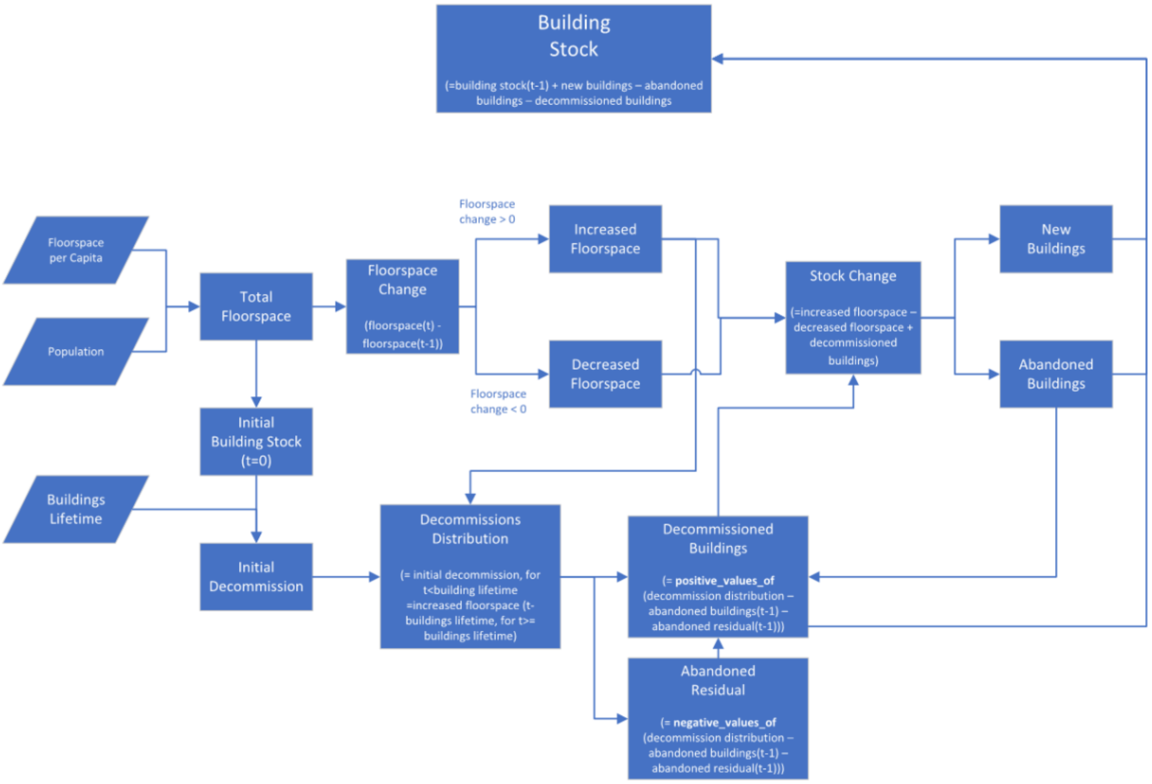


Figure 18 Design of the Building Stock Model (part of the TIMER REMG model)

The Insulation module (Figure 19) uses the different groups of the buildings stock to simulate the investment decisions of the residents based on the relative cost of improving the energy efficiency of building envelopes through insulation. These investments in insulation are possible during the construction of new buildings and during the renovation of older buildings. Specifically, there is a decision between six possible insulation levels, ranging from "very low" to "zero energy building" equivalent. In the case of older buildings there is a second decision to determine if the buildings will undergo renovation. Each insulation level has its own investment costs and thermal properties. The decision to invest in insulation is based on economic factors, such as the investment cost of insulation installation, different discount rates of the economic quintiles, and the benefits of increasing in insulation through reduction of fuel consumption. Furthermore, behavioural and preference aspects are incorporated in these economic decisions in the form of a premium cost. The outcome of this module are different insulation levels applied to the building stock's sub-groups allowning for an estimation and future projection of the average stock's useful energy intensity. This intensity is later used by other residential modules for the projection of the sector's energy demand and CO_2 emissions.

The Appliances module provides a detailed representation of the electric appliances used in residential buildings. The devices represented are fans, air coolers, air conditioners, refrigerators, microwaves, washing machines, clothe dryers, dish washers, TVs, VCR/DVD, and PCs. Decicive factors are acounted for such as, the diffusion of the appliances in different regions and income classes, the outage of power, the device efficiency, and potential subsidies enabling the estimation of the total electricity required by appliance type, region, and income class; thus, contributing in projections of the total energy demand and emissions of the residential buildings.

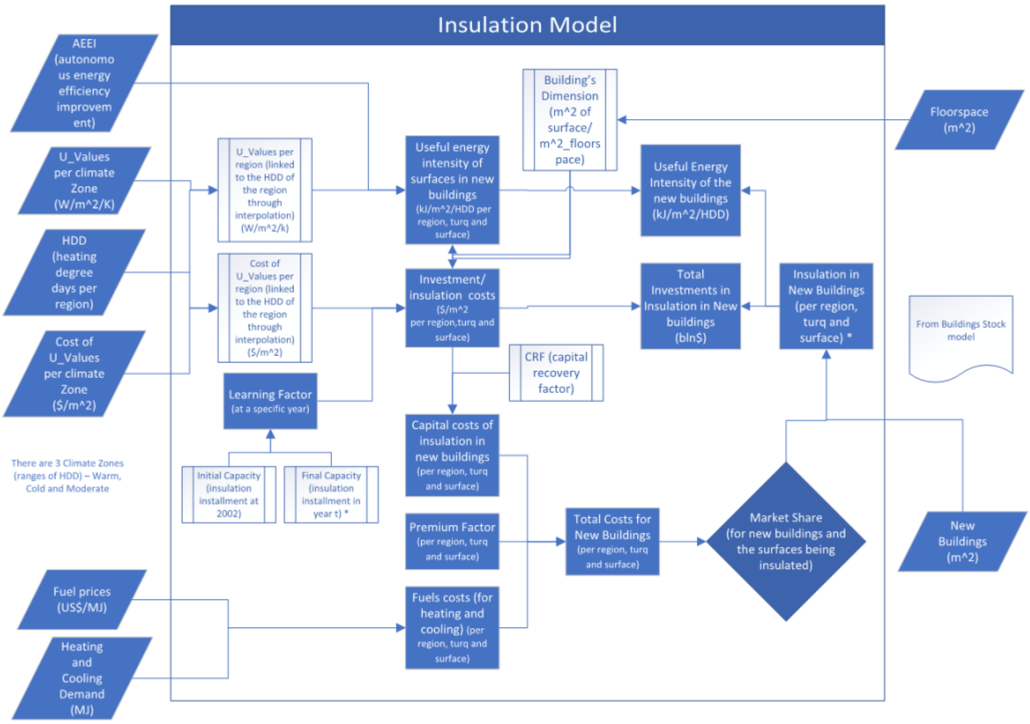


Figure 19: Design of the Insulation Module (part of the TIMER-REMG model).

Improving EU policies implementation in the IMAGE model

Scenarios developed in the SENTINEL project consist of a 'current trends' scenario that represents the current implementation of the 2030 climate and energy framework (see also Appendix A: IMAGE EU policy scenarios). Although, the EU has already put forward a plan to increase the emission reduction target from -40% to -55% the current framework has not been updated yet. Some of the key policies in the framework are the Emission Trading System (ETS), CO_2 emission standards for vehicles, and the (amended) Energy Performance of

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Buildings Directive. See *Appendix A: IMAGE EU policy scenarios* for the full list of EU policies that have been implemented in the IMAGE/TIMER model. Some overall multi-sector policy goals, such as the renewable energy target are only checked after model implementation of individual policies that would need to ensure achieving this.

The starting point is the current policies scenario for G20 countries that was developed in the CD-LINKS project (CD-LINKS, 2017; Roelfsema et al., 2020). It includes implemented policies that have been accepted by the parliament or through executive orders. In the SENTINEL project, this implementation has been updated for the EU by improving the Building code for new buildings, CO_2 standards for cars, and adding the heavy-truck standards.

Building code

One of the main policies that is part of the Building Directive is the European Net-Zero Emissions Building (NZEB) policy. This prescribes that every new building from 2021 onwards must be nearly zero-energy building. A NZEB according to the Energy Performance of Buildings Directive (EPBD) is a building with a very high energy performance; thus, resulting in a low energy demand. Furthermore, this demand should be covered primarily by on-site renewable sources or other nearby sources.

Having the EPBD definition in mind we implemented the NZEB's in the residential module of TIMER. From 2021 onwards the new buildings in Europe have some "forced" distinct characteristics. First, the insulation level is enhanced improving their envelope's efficiency. Then, heat pumps are installed in buildings to cover their heating demand efficiently. Finally, PVs (photovoltaic solar panels) are installed on the rooftops of buildings to sustainably cover their low energy demand. The PV installation is endogenously limited by its potential prescribed by the model.

CO_2 vehicle performance standards for cars and trucks

The IMAGE transport module includes different transport modes for travel and freight transport. The modes for which we have implemented policies are cars and heavy trucks. The freight module also contains medium trucks; but these have not been included in the implementation as more insights are necessary on how to map EU transport modes to the IMAGE transport modes[13].

The CO_2 performance standard for cars sets a fleet-wide standard for new car registrations. This means that car manufacturers are obliged to make sure that the average CO_2 emissions of their sold cars per year meet a certain target. This target is defined in terms of tailpipe emissions; so, it does not include secondary emissions from electric vehicles (EVs). The target

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[13] See https://www.transportpolicy.net/standard/eu-vehicle-definitions/

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for 2021 is set to 95gCO_2/km. Furthermore, the 2025 and 2030 targets are set relative to this year and aim for a fleet-wide reduction of 15% by 2025 and 37.5% by 2030. The same method is applied for the heavy-truck standards.

The CO_2 standard for cars is implemented in the IMAGE model by increasing the energy tax on fossil fuels to the level that the average CO_2 intensity for new cars is equal to the target. By increasing the energy tax, the model changes the annual composition of new cars, in comparison to the reference scenario and favours non-fossil fuelled cars. The CO_2 intensity for gasoline and diesel cars is shown in Figure 20. In practice car manufacturers will achieve these targets by improving the efficiency of existing fossil-fuel cars and by developing electric or hydrogen cars. The implementation of both measures at the same time in the TIMER model is not feasible; thus, we have only modelled the switching to more efficient car types, but did also include the low emissions (e.g., electric cars) share targets that are part of the European Strategy for low-emissions mobility. As the energy use for cars in TIMER is described in terms of MJ/pkm, the CO_2 intensity of cars needs to be calculated in terms of gCO_2/km. For this we have made the following assumptions:

- CO_2 intensity fuels is calculated based on the assumption that there are only gasoline and diesel cars, and they have a fixed ratio (gasoline=43%4). This CO_2 intensity is also used for biofuel and gas fuelled cars. In addition, electric cars have no tailpipe CO_2 emissions.

- For this calculation, we use a CO_2 intensity for gasoline of 2.4 g CO_2 /l, and CO_2 intensity for diesel of 2.7 g CO_2 /l, the resulting assumed energy intensity for these fuels is 34.841 MJ/l.

- The average load for cars is 1.6 persons

Figure 20 shows the impact the standards on CO_2 intensity, and compares it with historical data of the European Environment Agency (2017) and the Odyssee-MURE (n.d.) database. The average CO_2 -intensity of new cars by 2030 improves from 102.8 to 58.8 gCO_2/km.
In addition, the benchmarks for low emission vehicles (electric cars) were implemented in the IMAGE model by enforcing this share in the model. The credit system as part of the CO_2 performance standard was not explicitly included in the assessment. The focus for implementation in the IMAGE model was 2030, and the 2020 target was therefore overachieved.

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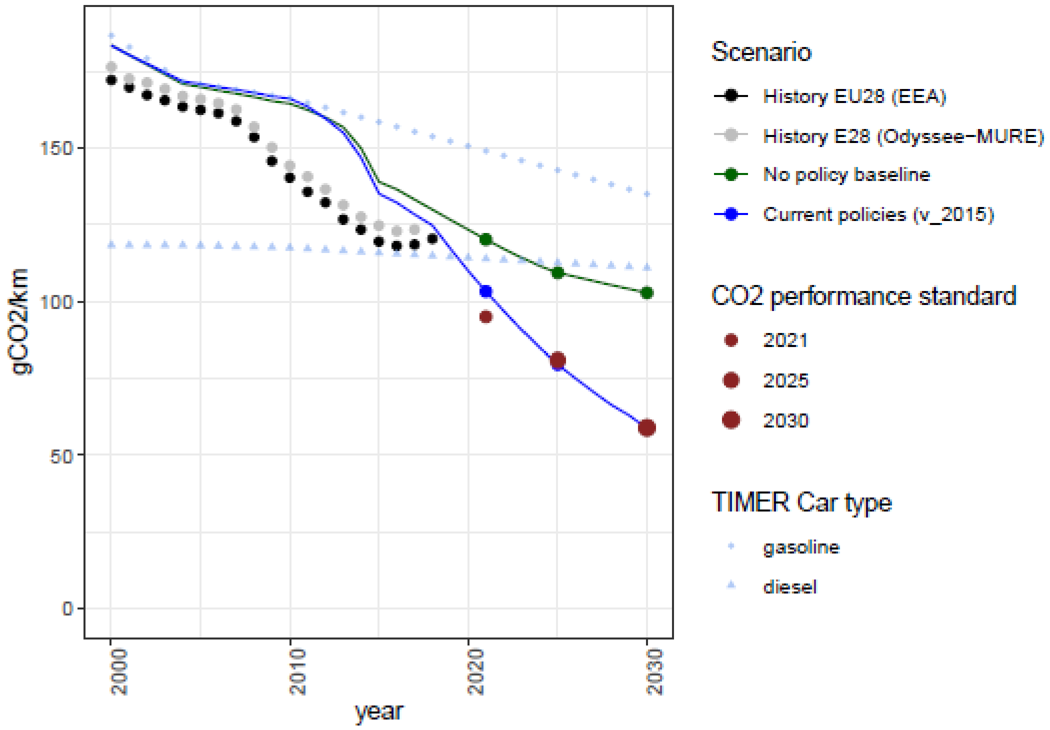

Figure 20 CO_2 standards implemented in the TIMER. model

Future developments

Although this deliverable details some model developments, there are many developments remaining for the three energy system planning models. In particular, EnergyPLAN aims to improve its geographical representation, through linking with IMAGE and Euro-Calliope as well as integrating with a GIS module to generate demand and supply data. A longer term goal is to enable EnergyPLAN to better model the transport sector, by combining a number different zero-emission technologies to better assess the right mix of fuels. EnergyPLAN already includes detailed methanation and Power-to-X solutions, but Fischer-Tropsch, Pyrolysis and Hydrothermal Liquefaction technologies have yet to be included. To better link to policy-relevant scenarios, Euro-Calliope aims to represent deployment through time. Deployment through time will allow Euro-Calliope to consider the dynamics of technology deployment pathways from now to 2050, and how they impact scenario viability; these results will be directly comparable with those from IMAGE.

The IMAGE model will continue with increasing transparency by extending the Python pilot to also implement the remaining residential building modules. To ensure operation of the IMAGE model, an interface will be developed to link the new residential model to the existing IMAGE model. This is dependent on the technical possibilities in the MyM language, which are currently being explored. Additionally, a key EU policy instrument that has not been implemented in the IMAGE model is effort sharing. We will investigate whether this is possible to implement with the FAIR model (den Elzen et al., 2014). With this method, a carbon tax will be applied to the two Europe regions and, if possible, to a subset of sectors.

All models will also be developed to facilitate intra- and inter-module linkage. This will entail the development of processing scripts to translate data into and out of the SENTINEL data package format. With this development, we will be able to better harmonise datasets as well as soft link to environmental assessment and social constrains tools (Work package 2), demand models (Work Package 3), and economic assessment models (Work Package 5).

Scope for model linkage

We have identified potential model linkage within the three energy system planning modules, which capitalise on model development and aim to address policy-relevant issues. These linkages include:

- **Euro-Calliope** can provide sector-coupled system designs for select European countries, to be simulated in greater detail in **EnergyPLAN**.
- **IMAGE** can provide environmental impact indicators/limits to act as parameters/constraints in **Euro-Calliope**.
- **IMAGE** and **Euro-Calliope** can align on pathways in their analysis of the optimal configurations of the future European energy system.

- **EnergyPLAN** can provide simulation results to **Euro-Calliope**, for the effects of interconnection between regions to be assessed.
- **IMAGE** can provide global boundary conditions to both **Euro-Calliope** and **EnergyPLAN**, including available bioenergy crops and carbon emissions budgets.
- **IMAGE and Euro-Calliope** can compare optimal European deployment pathways, once remaining model development is completed. These pathways can be complimented by **EnergyPLAN** simulating regional deployment in select years between 2030 and 2050.

These intra-module links will be investigated within the scope of the different case studies being prepared within Work Package 7. Each link will be formed to maximise relevant insights in the context of select case study research questions.

There is also scope for linkage to models in other SENTINEL modules. Notably, we plan to input socio-political constraints from the QTDIAN model, environmental parameters from the ENVIRO framework, and scenario-focussed demand data from the models DESSTINEE and DREEM. Our results will then act as inputs to economic impact models such as WEGDYN. Model linkage in both directions is predicated on the development of data communication channels using the upcoming SENTINEL data package format.

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Appendix A: IMAGE EU policy scenarios

EU climate-, energy and land use policies. I=implemented, C=checked, NI=not implemented in IMAGE/TIMER model.

Sector	IMAGE	Policy	Coverage sectors	Policy goal
Economy-wide	C	Energy Efficiency Directive	Economy-wide	20% energy efficiency improvement target for 2020
				=1483 Mtoe of primary energy or 1086 Mtoe of final energy
	C			32.5% energy efficiency improvement in 2030
				=1273 Mtoe of primary energy and 956 Mtoe of final energy
	NI	Effort sharing	Non-ETS: transport, buildings, agriculture, waste	10% reduction in total emissions from the sectors covered by 2020 compared with 2005 levels
				and of 30% by 2030 compared with 2005 levels
	C	Renewable Energy Directive	Economy-wide	At least 32% of final energy consumption by 2030
	I	F-gas Regulation	Economy-wide	By 2030 F-gas emissions are decreased by two-thirds compared with 2014 levels.

Energy supply/industry	I	Emission Trading System		In 2020, emissions from sectors covered by the system will be 21% lower than in 2005
				In 2030, emissions from sectors covered by the EU ETS will be cut by 43% from 2005 levels
	NI	Innovation fund		ETS revenues are invested in innovations
Transport	I	CO2 performance standards cars and vans	cars	Average fleet-wide standard for new registrations of 95 gCO2/km in 2021
				15% reduction of average fleet-wide standard of new registrations relative to 2021 by 2025
				37.5% reduction of average fleet-wide standard of new registrations relative to 2021 by 2030
				15 % low emissions share of the new passenger cars by 2025
				35 % low emissions share of the new passenger cars by 2030

	NI		vans	Average fleet-wide standard for new registrations of 147 gCO2/km in 2020
				15% reduction relative to 2021 by 2025
				31.5% reduction relative to 2021 by 2030
				15% reduction of average fleet-wide standard of new registrations relative to 2020 by 2025
				30% reduction of average fleet-wide standard of new registrations relative to 2020 by 2030
	I	CO2 performance standards trucks and busses	large lorries	Start 2021
				15% reduction relative to 2020 by 2025
				30% reduction relative to 2020 by 2030
				Credit system for low emission trucks
			smaller lorries, buses, coaches and trailers.	Start 2023
				Targets are not decided yet

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	I	Renewable Energy Directive		10 % share of energy from renewable sources in transport in Community energy consumption by 2020
				Renewable energy for final consumption of energy in the transport sector is at least 14 % by 2030
	NI	Fuel Quality Directive		Reduction of the greenhouse gas intensity of transport fuels by a minimum of 6% by 2020
				on a life-cycle basis against a 2010 baseline of 94.1 gCO2eq/MJ
				Biofuels sustainability criteria
	NI	Car Labelling Directive		Labelling
	NI	Shipping Strategy		Labelling
				Supporting IMO greenhouse gas strategy
		Emission Trading System (Aviation)		CO_2 emissions from aviation have been included in the EU ETS) since 2012 (flights within EU)
Buildings	I	Buildings Directive		all new buildings must be nearly zero-energy buildings (NZEB) from 31 December 2020

	NI			Since 31 December 2018, all new public buildings already need to be NZEB
	NI			Energy efficient renovations to at least 3% per year of buildings owned and occupied by central governments
	I			Minimum energy efficiency standards and labelling for appliances
AFOLU	NI	Effort sharing (LULUCF)		Net LULUCF emissions for each MS are zero or lower
				The scope is extended from only forests today to all land uses (and including wetlands by 2026)