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

Topic: LC-SC3-CC-2-2018 of the Horizon 2020 work program: *Modelling in support to the transition to a Low-Carbon Energy System in Europe*

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

Project number: *837089*

Project name: *Sustainable Energy Transitions Laboratory*

Project acronym: SENTINEL

Start date: 01/06/2019 **Duration: 36 months**

Deliverable reference number and title:
D 2.5 Integration of socio-technological transition constraints into energy demand and systems models

Version: 1

Due date of deliverable: 09.2021 **Actual submission date: 5.10.2021**

Dissemination Level		
PU	Public	X
CO	Confidential, only for members of the consortium (including the Commission Services)	
EU-RES	Classified Information: RESTREINT UE (Commission Decision 2005/444/EC)	
EU-CON	Classified Information: CONFIDENTIEL UE (Commission Decision 2005/444/EC)	
EU-SEC	Classified Information: SECRET UE (Commission Decision 2005/444/EC)	

Integration of socio-technological transition constraints into energy demand and systems models

October 2021

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Please cite as:
Süsser, D., Pickering, B., Chatterjee, S., Oreggioni, G., Stavrakas, V., Lilliestam, J. (2021). Integration of socio-technological transition constraints into energy demand and systems models. Deliverable 2.5. Sustainable Energy Transitions Laboratory (SENTINEL) project. Potsdam: Institute for Advanced Sustainability Studies (IASS). DOI: 10.48481/iass.2021.030.

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Abbreviations, acronyms, and units

CSP	Concentrated Solar Power
CO_2	Carbon Dioxide
DESSTINEE	Demand for Energy Services, Supply and Transmission in EuropE
DK	Denmark
DREEM	Dynamic high-Resolution dEmand-sidE Management
EE	Energy Efficiency
EU	European Union
ETS	Emission Trading System
GHG	Greenhouse Gas
GW	Gigawatt
HIB	High Efficiency Buildings
IS	Iceland
JRC	Joint Research Centre
Mtoe	Million tonnes of oil equivalent
MW	Megawatt
NECP	National Energy and Climate Plan
NO	Norway
NTC	Net transfer capacity
PAC	Paris Agreement Compatible
PV	Photovoltaic
QTDIAN	Quantification of Technological DIffusion and sociAl constraiNts
RE	Renewable Energy
SENTINEL	Sustainable Energy Transitions Laboratory
SE	Sweden
TWh	Terawatt-hour
TYNDP	Ten-Year Network Development Plan
WP	Work Package

Glossary

A "*Logic*" is a general rule about where and which renewable infrastructure should be built. It is a thought-puzzle adding to the "*Storylines*"/ "*Narratives*."

A "*Narrative*" is a story or description of a situation or series of events. In the context of energy modelling, it describes a detailed possible energy future, and the term is interchangeably with "*Storyline*".

A "*Storyline*" is a qualitative narrative describing a detailed possible energy future.

A "*Social Storyline*" is a "*Storyline*" describing societal developments and interactions and interdependencies between actors, technologies, and policy interventions in the context of the energy transition.

A "*Scenario*" is a quantitative description of a possible, alternative energy future, compared to a reference or baseline, and is typically used to provide information on how to reach a certain goal.

A "*Pathway*" is a quantitative trajectory of a "*Scenario*" that departs from 'reference futures', or 'business-as-usual'.

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Executive summary

The decarbonisation of the European energy system is a large-scale transformation, which demands not only for a techno-economic feasibility analysis, but also for an assessment of the social and political feasibility and environmental impacts. However, most energy models are not able to fully represent the social and political developments and dynamics of the energy transition, such as preferences, acceptance and behavioural changes of citizens and decision-makers. To address this shortcoming, we developed QTDIAN (Quantification of socio-Technological DIffusion and sociAl constraiNts) – a toolbox of qualitative and quantitative descriptions of socio-technical and political aspects of the energy transition. In this deliverable, we present and discuss the linking of QTDIAN with the energy demand models DESSTINEE, HEB and DREEM, and the energy system model Euro-Calliope. The purpose of linking the models is to integrate the outputs from QTDIAN into the energy models to allow for an empirically based and thus more realistic analysis of energy system trajectories, with a higher relevance for informing pending policy decisions. The central question we address is: *How can the social storylines and quantifications from QTDIAN be transferred into energy demand and systems models?* We show several ways how QTDIAN's quantified variables allow for a direct application of the storylines into the modelling process of Euro-Calliope, DESSTINEE, HEB and DREEM. The qualitative storylines ensure that modellers do not create technically feasible energy systems that are outside the realms of social or political realities. In addition, the quantitative data can be used to improve the accuracy and especially the policy relevance of the modelling results by providing specific estimates for social and political variables and constraints. However, not all aspects of QTDIAN could be integrated because not all aspects of the storylines could be quantified, and the models to which QTDIAN links in this deliverable are not able to capitalise on all QTDIAN outputs. We identified further requirements for data, including different temporal and spatial scales. We conclude that the linking of QTDIAN with energy demand and energy systems models is a promising approach to better represent socio-political drivers and barriers for technology changes and climate change mitigation measures. We will run the models with the integrated linkage with QTDIAN to evaluate the outcomes and added value of the linking in the context of SENTINEL case studies (WP7).

1 Introduction

European countries need to fully decarbonise their energy systems over the next investment cycle to reach climate neutrality. This implies a need for entirely or almost entirely renewables-based energy systems. The transition to renewables is a large-scale transformation, changing the way how we produce, transmit and consume energy. Within, citizens are supposed to play a much larger role as self-consumers and participants in energy communities (European Parliament, 2018). Thus, they (will) shape changes in the energy system, impacting both energy demand and supply. For this reason, and especially because of the time element, we need transitions that are not only technically or economically feasible, but also socially and politically feasible, taking preferences, acceptance and behavioural changes of citizens and decision-makers into account (Cherp et al., 2018).

Most energy models are, however, not able to fully depict the social and political developments and dynamics of the energy transition, despite the increasing awareness that non-technical factors are critical for the energy transition (Bridge and Gailing, 2020; Fast, 2013; Miller et al., 2013). Most models are not able to represent social behaviour and actors' heterogeneity, the effect of social acceptance and community ownership, the impacts of different policy choices on energy outcomes, and the effects of transformation dynamics (Köhler et al., 2018; Koppelaar et al., 2016; Krumm et al., 2022; Pfenninger et al., 2014; Süsser et al., 2021a), which makes these models far from being realistic (Trutnevyte et al., 2019; Turnheim et al., 2015). Increasing research efforts have been made to reflect these social realities of the energy transition in energy models by linking social science and computer-based modelling (Geels et al., 2016; Halbe et al., 2015; Hirt et al., 2020; Trutnevyte et al., 2019; Turnheim et al., 2015). In fact, translating qualitative storylines into numeric inputs is a huge challenge. Our work contributes to this research stream by demonstrating how socio-political storylines and empirical data can be used to improve existing energy models.

In SENTINEL, we develop ways to incorporate social and political factors into energy models, so that they are included into the insights we give on the future of the European energy system. We have identified the better representation of behavioural and social aspects of the energy transition in modelling as a central user need (Gaschnig et al., 2020). In response to this, we developed QTDIAN (Süsser et al., 2021a), which is a toolbox of qualitative and quantitative descriptions of socio-technical and political aspects of the energy transition that influence the overall potential, the rate of energy-related technology and service diffusion and the design of the future energy system. It consists of **(i)** qualitative social storylines of the energy transition rooted in observed social and political developments and dynamics of the energy transition, and **(ii)** quantifications for social, technical, and political aspects of the energy transition to be integrated in energy models, such as energy system and energy demand models.

In this deliverable, we present and discuss the linkage of the energy modelling toolbox QTDIAN (WP2) with the energy demand models DESSTINEE, HEB and DREEM (WP3), and the energy system model Euro-Calliope (WP4). The purpose of linking the models is to integrate the outputs from QTDIAN into the energy demand and systems models to allow for an empirically based and, thus, more realistic analysis of energy system trajectories. The central question we address is: *How can the social storylines and quantifications from QTDIAN be transferred into energy demand and systems models*?

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2 Output from QTDIAN

QTDIAN (Quantification of socio-Technological DIffusion and sociAl constraiNts) is a modelling toolbox of qualitative and quantitative descriptions of social and political drivers and constrains of the energy transition (Süsser et al., 2021a), developed at the Institute for Advanced Sustainability Studies (IASS) Potsdam. The main objective of the toolbox is to provide socio-political storylines and empirical data for existing energy models that can improve the representation of social and political aspects in these models. QTDIAN has two types of outputs:

- Social storylines that are based on transitions theory and empirical observation of actual social/ political drivers and barriers in the European energy transition.
- Empirical quantitative data for a range of key social/ political parameters, to be used:
  - In conjunction with the storylines for which we provide suggested data modifications, adapting the empirically observed "today" data according to the logics of the storylines.
  - Adapted in the way modellers see as appropriate for their particular scenarios and research questions.

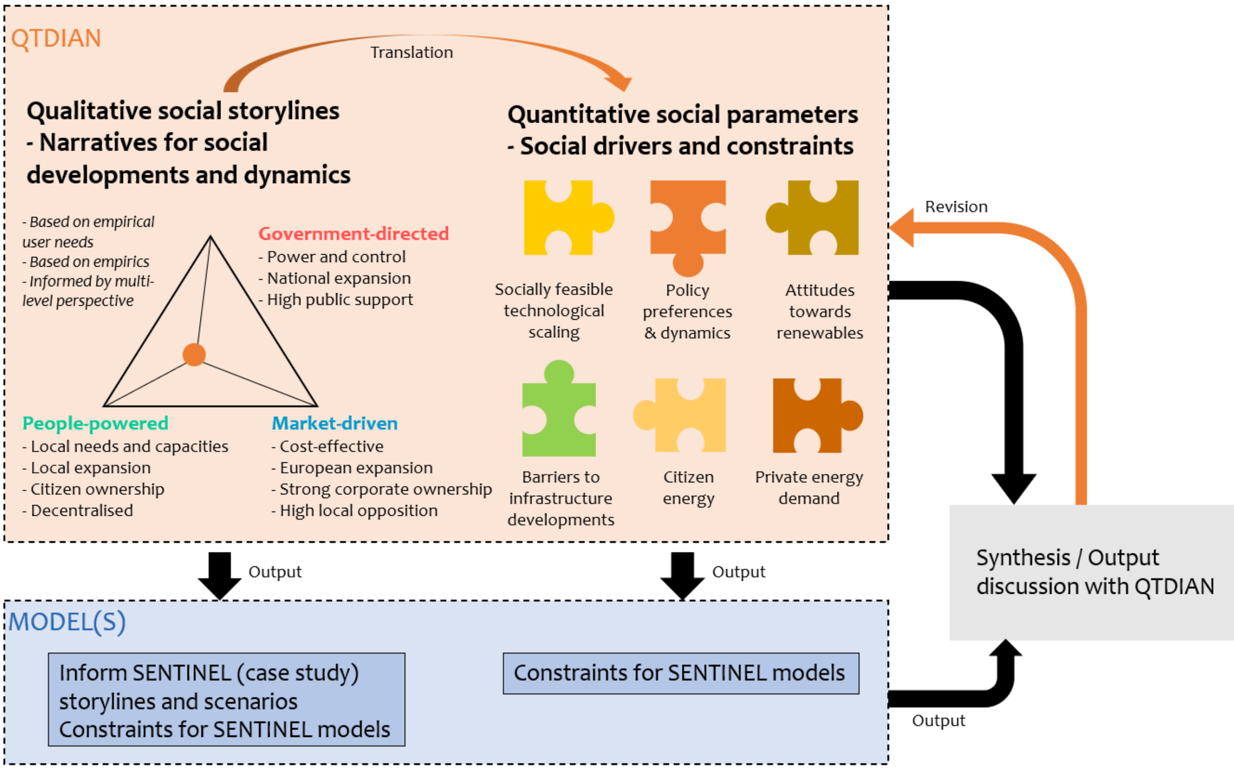

Figure 1: Overview of the QTDIAN modelling toolbox. Source: own figure from D2.3, Süsser et al., 2021a.

A main contribution is that QTDIAN provides actual, empirically observed quantifications, so that modellers can make their scenarios close to reality and not have to guess how important a societal or political factor may be. For example, is a transmission line project delayed by 3 months, 3 or 30 years? Is the potential for prosumerism in the EU 5%, 20% or 50% of installed capacity? Is the annual building renovation rate across the EU 0.3%, 1% or 3%? Or did consumption of appliances increase or decrease, and how could that trend be related to future energy consumption? Concrete quantitative parameters provided by QTDIAN are listed under **Section 2.2**.

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2.1 QTDIAN social storylines

The QTDIAN storylines provide a theoretically and empirically founded understanding for societal drivers and constraints of the energy transition. In comparison to existing storylines, which typically focus on technological and economic aspects, QTDIAN *social* storylines are based on governance logics and have the needs, preferences and capacities of citizens and their role within the energy transition at its core. The three social storylines can be applied to broaden the perspectives of transition storylines and pathways and to translate storylines features/ variables into model assumptions. Table 1 presents the social storylines and their key features/ variables. A more detailed description of the storylines can be found in D2.3 (Süsser et al., 2021a).

Table 1: Three social storylines of the energy transition (RE = renewable energy; EE = energy efficiency), updated table from D2.3, Süsser et al., 2021a.

Storyline features/ variables	People-powered	Government-directed	Market-driven
Summarising description	People drive the transition by becoming individual and collective (co-)owners of RE. People benefit from the transition, which mainly happens regionally. The energy system is characterised by decentralised RE and minimal grids. There is a "Renewable Energy First"-mentality.	The government directs the energy transition, which mainly happens nationally. General public support is high but so is partially local opposition. Society is less involved in the transition. The government's "Energy efficiency first" philosophy decreases energy consumption.	Market actors and new technologies drive the energy transition guided by cost-effectiveness concerns. The transition happens with a continental scope. Society does not play a large role in the energy transition. Local opposition against large-scale projects is high. The energy system is characterised by a centralised generation and transmission.
Problem definition today	Energy system is characterised by fossil-nuclear complex and centralised power structures, and undemocratic energy supply.	Emissions are too high because we use the wrong technologies and have the wrong practices.	Energy transition risks being overly expensive, if governments interfere too strongly with the market.
Solution	Break up existing centralised structures; build driven by and for citizens, cooperatives, municipalities	Reduce emissions by replacing production assets and fuels with carbon-free ones; all while always maintaining security of supply and controlling direction of transition	Governments push for pricing in external effects, set long-term climate target, and then leave it to the market to find efficient solution.
Main decision/ system planning "logic"	Local needs & capacities; regional expansion logic	Security & control; national expansion logic	Cost-effectiveness; European expansion logic
Where do we want to go?			
Energy system 2050	climate-neutral, mainly renewable-energy-based		
Resulting social system design:			
Actor diversity	High diversity with many small and medium size companies, cooperatives, and municipal utilities	Medium diversity with private and public utilities	High market actors (no citizens, no public utilities)
Ownership of renewables: individuals and community energy	High local citizen participation and (co-)ownership, with many prosumers	Public and private utilities as central enactors; bottom-up initiatives and citizen energy is not strongly represented	Private companies dominate ownership of infrastructure
Household's electricity consumption of appliances and lightening	Slight decrease as current trend	High decrease - "EE first"	Constant (market-driven increase of new appliances and use cases)
Energy efficient building renovation	Low renovation rate (RE First)	Very high renovation - "EE first"	High building renovation rate (cost-effective first)
Resulting tech system design:			
Centralisation vs. decentralisation	Decentralised, small units	Mainly centralised, larger units	Centralised, larger units

Storage	Decentralised storage (e.g. batteries) as main balancing option	Grid-scale storage, national transmission	Balancing through European transmission, large-scale storage
Grid infrastructure	Minimised/ no new, regional focus	As much as needed, national focus	Much, European focus
Electricity transmission	Regional transmission, without new transmission	Mostly national, with transmission	European and beyond, with much transmission
Mobility	Shared solutions are common; expansion of public transport; fewer, decarbonised cars	Transport systems change only moderately; expansion public transport; the number of cars on the street remains largely constant	Little emphasis on public and communal solutions; public transport is hardly expanded, and personal mobility remains car-based
How do we get there? Drivers/ barriers			
Public participation and investments	High public participation and private investments in RE	Just Transition Mechanism has pushed investments; community projects have stopped due to unfavourable policy changes	Transition happens in the market, and industry finances large scale projects
Social movements	Strong climate movement; weak local anti-movements	Strong climate movement; medium to strong local anti-movements	Medium climate movement; strong local anti-movements
RE acceptance: public, local, market	Local and public acceptance is high for small-medium-scale projects; market acceptance is low for small-scale projects	Public high for general transition; local low for large-scale	Local low for large-scale projects; market high for large-scale projects
Opposition against projects	Low against small scale RE, local grids and solutions; no serious delays; high against large-scale and transmission, delays and cancellations	High opposition with significant delays, but few cancellations as governments override opposition	High opposition with significant delays, some cancellations as governments do not interfere to overcome opposition
Climate and energy policy	Ambitious policies, supporting individuals, communities, and smaller enterprises to take ownership of the energy transition	Ambitious national climate and energy policies	Sector-spanning carbon price; few climate policies in place supporting markets, not individuals and communities

2.2 QTDIAN quantitative parameters

The second output from QTDIAN is quantitative parameters. Here, we provide quantifications for six themes, or indicators, that are based on features of the social storylines. **Table 2** summarises the indicators and quantitative parameters. Note: Data are available for different geographical areas and time scales, depending on the data source. Detailed descriptions of the qualifications can be found in D2.3 (Süsser et al., 2021a), and the datasets are available at Zenodo (Süsser et al., 2021b).

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Table 2: Model input parameters.

Indicator	Model input parameters	Unit of the data	Region available	Data source
Socially feasible technology scaling	Maximum change rate: Installed combustible capacities	Capacity growth [GW/year] Maximum change rate over 5 years [MAX $(GW/year_t)$ / $(GW/year_{t-5})$] System change per year [% of total system capacity added/year]	EU 28+ World countries and areas World countries and areas	Eurostat, 2019 UN, 2021 IRENA, 2021
	Maximum change rate: Installed wind power capacity (onshore and offshore)	Capacity growth [GW/year] Maximum change rate over 5 years [MAX $(GW/year_t)$ / $(GW/year_{t-5})$] System change per year [% of total system capacity added OR removed/year]	EU 28+ World countries and areas World countries and areas	Eurostat, 2019 UN, 2021 IRENA, 2021
	Maximum change rate: Installed solar PV capacity	Capacity growth [GW/year] Maximum change rate over 5 years [MAX $(GW/year_t)$ / $(GW/year_{t-5})$] System change per year [% of total system capacity added/year]	EU 28+ World countries and areas World countries and areas	Eurostat, 2019 UN, 2021 IRENA, 2021
Policy preferences	Total GHG reduction targets	Emission reduction in percentage [%]	EU, 5 Nordic countries, Greece	EU strategies and NECP
	ETS sector reduction targets; Non-ETS sectors emission reduction targets	Percentage [%]	EU, Denmark, Sweden	EU strategies and NECP
	Renewable energy targets	Percentage in gross final energy consumption Percentage in gross final electricity consumption/ production [%] Percentage in gross final consumption for heating and cooling [%] Percentage in gross final consumption in transport [%]	EU, Denmark, Finland, Sweden, Greece	EU strategies and NECP
	Installed renewable power capacity	Capacity in GW and %	Greece	EU strategies and NECP
	Fossil fuel targets/ phase-out	Phase-out year	EU (PAC scenario), Denmark, Finland, Greece	EU strategies and NECP
	Installed gas power capacity	In GW	Greece	EU strategies and NECP
	Share of installed electricity capacity	Percentage [%]	Greece	EU strategies and NECP
	Energy efficiency improvements	Energy intensity in percent compared to forecast [%] Energy consumption in Mtoe	EU, Sweden, Greece	EU strategies and NECP

	Targeted cumulative energy savings	Mtoe (2021-2030)	Greece	EU strategies and NECP
	Final energy consumption	Percentage per year [%] OR in Mtoe Percentage of sources [%] OR TWh	EU, Greece, Finland	EU strategies and NECP
	Heating demand	Percentage [%]	EU	EU strategies and NECP
	Cross-border interconnection NTC	Percentage of yearly power production [%]	EU	EU strategies and NECP
	Energy storage: installed capacities	Energy [TWh] and capacity [GW]	Greece	EU strategies and NECP
	Residential building renovation	Percentage per year [%] OR #	EU, Finland, Greece	EU strategies and NECP
	Electric mobility	Number of passengers of electric cars OR Percentage of electric cars sold [%] OR Year of stop selling diesel and petroleum cars OR Percentage of renewables [%]	EU, Denmark, Norway, Greece	EU strategies and NECP
	Regulations/ recommendations on minimum distances onshore wind and housing,	Distance in meters	EU	OpenGov, 2021
	Regulations on density of wind turbines in municipalities	Density in percent [%]	Greece	JRC 2018 Report, Dalla-Longa et al., 2018
Preferences for renewable energy	Personal stance about different renewable technologies	Percentage who support, or reject [%]	GER	Renn et al., 2020 Wolf, 2020
	Opinion about renewables in people's backyard	Percentage who would like it, not like it, without previous experience, and with existing installations [%]	GER	Agency for Renewable Energy (Agentur für Erneuerbare Energien), survey by YouGov
Barriers to infrastructural developments	Onshore wind power development: Realisation duration, project litigation and duration of proceedings	Average realisation time from granting of the immission control permit to commissioning [months] Percentage of projects with litigation [%], and average duration of proceedings in months	Germany Germany	Fachagentur Windenergie and Land, Marktstammdatenregister Fachagentur Windenergie an Land (Quentin, 2019)
	Grid development (transmission and storage): expected amount/capacity; project delays	Total number of projects expected to be commissioned, and total length (km) of projects and storage capacity (GWh), respectively Percentage of projects delayed [%] Delays in months	EU 28	ENTSO-E TYNDP 2020 Projects Sheets ACER list of projects of common interest (PCI)

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Citizen energy	Citizen renewable energy ownership developments	Electricity production capacity in MW by autoproducers[1] for wind, PV, solar thermal, wave/tidal/ocean energy Percentage of capacity by autoproducers for wind, PV, solar thermal, wave/tidal/ocean energy [%]	EU 28 (some countries no data)	Eurostat
	Number of single family dwellings	Amount	EU 28	EU building data base
Energy demand	Renovate rates (floor area)	Annual energy renovation in residential buildings for the European countries (average 2012-2016)	EU 28	EU
	Size of housing	Average number of rooms per person, annual Average number of rooms per person, annual	EU 28 plus	Eurostat
	Total floor area of single and multi family dwellings	m²	EU 28	EU building data base
	Private energy consumption by end-uses	ktoe; shares [%]	EU 28	JRC-IDEES - Integrated Database of the European Energy System (2000-2015)
	Electricity consumption by end-uses	ktoe; kWh; shares [%]	EU 28	JRC-IDEES - Integrated Database of the European Energy System (2000-2015)
	Number of electric appliances	Amount; increase/decrease [%]	EU 28	JRC-IDEES - Integrated Database of the European Energy System (2000-2015)
	Final electricity consumption of appliances and lightening (sum)	ktoe; (kWh; increase/decrease [%])	EU 28	JRC-IDEES - Integrated Database of the European Energy System (2000-2015)

2.3 Quantitative assumptions for each of the storylines

The future is unknown, but we can make informed assessments of ideal-typical future developments based on past observations of trends and the factors that determined these trends. This is the basic premise of QTIDIAN: explore possible futures of a range of social and political parameters, informed by observations of how they have developed in the past. The storylines are designed to allow for quantification of additional social and political parameters not quantified here, should such parameters be required in future modelling efforts.

[1] Enterprises which produce electricity but for whom the production is not their principal activity.

2.3.1 Inputs for the system design model Euro-Calliope (WP4)

For each storyline, we assume different developments for policy targets, energy mixes and grid expansions, mobility, and distance/ density restrictions. **Table 3** summarises the key variables and quantifications.

Table 3: Potential input parameters for Euro-Calliope.

Storyline variables & values	**People-powered**	**Government-directed**	**Market-driven**
Total GHG reduction targets	65% reduction (GHG-1990) by 2030, net-zero by 2040 (PAC scenario[2])	>55% reduction (GHG-1990) by 2030 ('Fit for 55'[3]), 100% climate neutrality by 2050 (European Green Deal[4])	>55% reduction (GHG-1990) by 2030 ('Fit for 55'), 100% climate neutrality by 2050 (European Green Deal)
Renewable energy in gross final energy consumption	>50% by 2030, 100% by 2040 (PAC scenario)	40% by 2030 ('Fit for 55'), 100% EE by 2050	40% by 2030, > by 2050 (nuclear energy possible) ('Fit for 55')
Energy intensity	25% energy intensity decrease (compared to projection for 2030) by 2030	36-**39%** energy intensity decrease (compared to projection for 2030) by 2030, > by 2050 ('Fit for 55')	36-**39%** energy intensity decrease (compared to projection for 2030) by 2030, > by 2050 ('Fit for 55')
Fossil fuel phase-out	Coal by 2030 Fossil gas by 2035 Fossil oil by 2040 (PAC scenario)	Coal by 2038 (oriented on German target); Fossil gas and oil by 2050; Following the current trend (2011-2020), the consumption of solid fossil fuels[5] in the EU will be down to 200 Mt per year[6]	No fixed dates Coal capacity in 2030 cannot be higher than year's before
Cross-border electricity interconnection	<u><</u>5% in each hour (send and received from another country) by 2030	<15% of hourly exchange by 2030	≥15% of hourly exchange by 2030 (EU target[7])
Mobility: electric vehicles	fully electrified private car fleet by 2040 – up to half is electrified by 2030; 10% increase in # of passengers per vehicle by 2040 (compared to the baseline) (PAC scenario)	Phase-out fuel-based cars by 2030 (current trend of EU MSs between 2025-2040); 25% EV by 2030 (based on S-shape trend calculation of EEA[8])	Phase-out fuel-based cars by 2035 (Fit for 55 package)
Mobility: transport mode (distances)	>20% reduction in car use by 2040 (compared to the baseline);	<20% reduction in car use by 2040 (PAC scenario); 25% increase of rail freight between 2015 and	Transport modes remain the same; 0% reduction in car use

[2] CAN Europe and EEB, 2020: https://www.pac-scenarios.eu/fileadmin/user_upload/PAC_scenario_technical_summary_29jun20.pdf
[3] EC, 2021, COM(2021) 550 final; 'Fit for 55': delivering the EU's 2030 Climate Target on the way to climate neutrality https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:52021DC0550&from=EN
[4] EC, 2019, COM(2019) 640 final. The European Green Deal, https://eur-lex.europa.eu/resource.html?uri=cellar:b828d165-1c22-11ea-8c1f-01aa75ed71a1.0002.02/DOC_1&format=PDF
[5] hard coal, brown coal, coal products
[6] https://appsso.eurostat.ec.europa.eu/nui/show.do?dataset=nrg_cb_sff&lang=en
[7] https://ec.europa.eu/energy/topics/infrastructure/electricity-interconnection-targets_en
[8] Data from European Environmental Agency (EEA), Electric cars registered in the EU-27, Iceland, Norway and the United Kingdom, https://www.eea.europa.eu/data-and-maps/indicators/proportion-of-vehicle-fleet-meeting-5/assessment

	Doubling of rail freight between 2015 and 2040, and a 12% shift in passenger km from car to bus, train, walk and bicycle combine (PAC scenario)	2040, and a 6% shift in passenger km from car to bus, train, walk and bicycle combine	
Preferred energy sources / energy mix	As much roof-top solar as possible (lower bound of least 45%* of electricity capacity), to allow for high ownership OR just make almost all roofs single- and multi-family houses full (*amount overall renewables owned by German citizens today – mainly solar), doubling share for wind	'Best' balanced mix of technologies	As little land use/ demand as possible
Grid development transmission & actual transmission	Minimised, no new projects start, Projects currently (2021) under construction finished (TYNDP[9]); Regional transmission	As much as needed; 300 projects, 45,000 km by 2040 (planned TYNDP2020 projects[10]; transmission mostly national	Much – European focus; 400 projects by 2040; European and beyond, with much transmission
Grid-scale storage (batteries) projects	13 projects with 14,500 GWh storage capacity (planned TYNDP2020 projects)	26 projects with 29,000 GWh storage capacity (planned TYNDP2020 projects[11])	39 projects with 45,500 GWh storage capacity (planned TYNDP2020 projects)
Distances onshore wind and housing	500 meters for large turbines, 200 meters for small turbines (max 40 dB) (average minimum low in the EU, Dalla-Longa et al., 2018)	700 meters for large turbines and 200 meters for small turbines (<40 dB) (cf. JRC model recommendation section, Dalla-Longa et al., 2018))	1000 meters (average-high observed in the EU, Dalla-Longa et al., 2018)
Density onshore wind energy in municipalities	No restrictions	8% of municipal land area (found in Greece; OpenGov, 2021[12]	4% of municipal land area (found in Greece)

Explanation for each of the parameter values in the storylines.

In the market-driven scenario & partially also the government-directed, the assumed quantification for targets on **greenhouse reduction, renewable energy, energy intensity and interconnection** are based on current EU targets (COM/2019/640 final). In contrast, the people-powered storyline follows the assumption that the people demand for more ambitious climate action in line with the 1.5° limit. Thus, targets in these storylines are higher than in the other two and are based on targets of the PAC scenarios (Climate Action Network Europe and European Environmental Bureau, 2020), except the number for the energy intensity. We assume that the energy intensity reduction is higher in the Market-driven and Government-directed than in the People-powered storylines, as we aimed for higher differences between

[9] https://tyndp.entsoe.eu/maps-data
[10] https://tyndp2020-project-platform.azurewebsites.net/projectsheets
[11] https://tyndp2020-project-platform.azurewebsites.net/projectsheets
[12] http://www.opengov.gr/minenv/?p=10255

the stories. Cross-border interaction plays a much larger role in the Market-driven storylines, as it assumes a European expansion logic for renewables, as it assumes a European expansion logic for renewables to minimise costs for all, without looking at other criteria, while in the People-powered storyline, production and consumption are more local and follow a bottom-up logic.

Furthermore, the People-powered and Government-directed storylines set a clear end date for the **fossil fuel phase-out**, but the People-powered earlier than the latter. The Market-driven does not set any end date, as the market will decide when fossils become unprofitable. But we assume that coal capacities will be lower in 2030 than today.

In the People-powered storyline, **car use** will be largely reduced as citizens switch to other and shared modes of transportation, such as public transport. The remaining fleet will be electrified by 2040. The Market-driven storyline will trigger investments in electric cars, assuming a relatively stable overall use of cars. Furthermore, no new fuel-based cars will enter the market by 2035, based on the current EU targets. In the Government-directed storyline, fuel-based cars will be phased out earlier, and overall car use will be reduced.

In the People-powered storyline, citizens are often the project developers (or at least owners) and, hence, they largely **prefer** and **support technologies** where they individually or collectively benefit from owning technologies. Consequently, we assume a doubling of shares for solar PV as well as onshore wind, compared to the Government-directed storyline/ current trend, making wind and solar the central pillars of the energy transition, and lower the shares for other sources. For the Government-directed we assume a balanced mix of renewable energy sources, including municipal waste. In the Market-based storyline, industry does not care about public acceptance, but about getting projects done. Thus, they build technologies where it is cheapest but also where land use is lowest. This is because citizens cannot participate directly, they are more likely to prefer technologies that are not in their backyard and affect their local environment.

When it comes to the **grid development**, in the Government-directed storyline, the developments are aligned with the current expansion plans. In the People-powered storyline, we assume that opposition against new wind power projects is lowest, not holding delays and litigations completely, but rather reducing them, because citizens own it and benefit themselves directly or via the regional economy. The opposition against transmission, in contrast, is high, because the focus of the generation expansion is local, reducing the need and case for transmission. Hence, there are no new transmission projects. In contrast, the Market-driven storyline seeks to minimise costs, strongly focusing on transmission, so that this storyline eventually sees a stronger expansion of the transmission grid than the Government-directed storyline. People do not oppose transmission as such because they see that it reduces the cost, which is their primary aim.

In the People-powered storyline, citizens generally accept local renewable energy developments, also because they actively participate in projects and benefit from revenues. Hence, **setback distances** are low (500 meters), and no density restrictions apply. In the Market-driven storyline, acceptance for onshore wind power is weak, also because citizens are rarely involved in the projects that are built by corporations.

Therefore, we assume the average-large setback distance observed in the EU (1000 meters) for this storyline. The Government-directed storyline represents the middle ground between the two other storylines. Here, we suggest following the JRC assumptions for distances (40 dB at nearest building, 700 meters for large installations). We also assume that only 8% of the municipal area are available for onshore wind, as is the case in Greece for onshore wind priority areas. Due to local resistance, only half of this is assumed in the Market-direct storyline– which is in line with the restrictions for tourism areas in Greece.

2.3.2 Inputs for the energy demand models HEB, DESSTINEE and DREEM (WP3)

For each storyline, we assume different developments for energy consumption, building renovation, rooms per person, and share of single- and multi-family house. Table 4 summarises the key variables and quantifications.

Table 4: Storyline variables and quantifications for energy demand models; Note: the factor values are the same for the EU, Nordic and Greek case study if no differences are indicated.

Storyline variables & values	**People-powered**	**Government-directed**	**Market-driven**
Building renovation (residential, floor space)	Deep renovation rate of 0.2% annually; medium renovation of 1.1% (current trend[13])	Deep renovation rate of 2.1% annually, 0.9% medium renovation (Renovation rate of 3% of which 70% are deep renovations (PAC scenario))	Deep renovation rate of 3% annually (BPEI report)
Rooms per person	*EU case study:* House: 1.7, Flat: 1.2 (assuming trend for Belgium for the whole[14])	*EU case study:* House: 1.8, Flat: 1.5 (status-quo of the EU, 2019[15])	*EU case study:* House: 2.1, Flat: 1.9 (assuming trend for Lithuania and Hungary, respectively, for the whole EU[16])
	Nordic case study: House: 1.6, Flat: 1.5 (assuming IS and SE low, respectively, for all Nordic countries)	*Nordic case study:* House: DK: 2.1, IS: 1.5, NO:2.2, SE: 2.1 Flat: DK: 1.8, IS: 1.6, NO:1.9, SE: 1.6 (assuming status quo)	*Nordic case study:* House: 2.2, Flat: 2.0 (assuming NO high for all Nordic countries)
	Greek case study: House: -0.1, Flat: 0.9 (assuming decrease trend of 0.1 of Belgium)	*Greek case study:* House: 1.3, Flat: 1.3 (assuming status quo)	*Greek case study:* House: 0.3, Flat: 1.7 (assuming increase trend of 0.3 of Lithuania and 0.4 of Hungary)
Total floor area of single and multi -family dwellings	*EU case study:* Single: 13657344.8 m² (2016) (assuming status quo) Multi: 7163631.49 m² (2016) (assuming status quo)	*EU case study:* Single: increase by 0.61% annually (current trend) Multi: increase by 0.68% annually (current trend)	*EU case study:* Single: increase by 1.5% annually (current average trend of top 3 countries (except Malta))

[13] https://op.europa.eu/en/publication-detail/-/publication/97d6a4ca-5847-11ea-8b81-01aa75ed71a1/language-en/format-PDF/source-119528141
[14] http://appsso.eurostat.ec.europa.eu/nui/show.do?dataset=ilc_lvho03&lang=en
[15] http://appsso.eurostat.ec.europa.eu/nui/show.do?dataset=ilc_lvho03&lang=en
[16] http://appsso.eurostat.ec.europa.eu/nui/show.do?dataset=ilc_lvho03&lang=en

			Multi: increase by 2.3% annually (current average trend of top 3 countries (except Luxemburg))
	Greek case study: Single: 160792.9 m² (2016) (assuming status quo) Multi: 212390.53 m² (2016) (assuming status quo)	*Greek case study:* Single: increase by 0.2% annually (current trend) Multi: increase by 0.09% annually (current trend)	*Greek case study:* Single: increase by 0.4% annually (double current trend) Multi: increase by 0.2% annually (double current trend)
Private electricity consumption of appliances and lighting	Linear decrease as of today (EU)	Exponential decrease to meet 2030 target	Constant (market-driven increase of new appliances and use cases)[17]
Mobility: electric vehicles	fully electrified private car fleet by 2040 – up to half is electrified by 2030; 10% increase in # of passengers per vehicle by 2040 (compared to the baseline) (PAC scenario)	Phase-out fuel-based cars by 2030 (current trend of EU MSs between 2025-2040); 25% EV by 2030 (based on S-shape trend calculation of EEA[18])	Phase-out fuel-based cars by 2035 (Fit for 55 package)
Mobility: travelled distances	>20% reduction in car use by 2040 (compared to the baseline); Doubling of rail freight between 2015 and 2040, and a 12% shift in passenger km from car to bus, train, walk and bicycle combine (PAC scenario)	<20% reduction in car use by 2040 (PAC scenario); 25% increase of rail freight between 2015 and 2040, and a 6% shift in passenger km from car to bus, train, walk and bicycle combine	Transport modes remain the same as today; 0% reduction in car use

Explanation for each of the parameter values in the storylines.

In the Government-directed storyline, we assume a deep **renovation rate** of 2.1% and a medium renovation rate of 0.9% per year, in line with the PAC scenario. In the Market-driven storyline, we assume that all renovations are deep renovations. In both storylines we see targets of 3% in line with the overall EU target. In contrast, in the People-powered storyline, citizens are more likely to invest in renewables and are, therefore, less interested in carrying out building renovations. Thus, we assume the renovation rate remains as today. To make full climate neutrality more achievable despite the lower renovation rate, **the living space (rooms per person and total floor area)** in this storyline is lower than in the others, and we assume a decrease in living space – using the observed trend in Belgium of -0.3 rooms/person over five years for flats and -0.1 rooms/person in houses – for the whole EU.

In the Market-driven storyline, we assume that the markets will drive people's desire for a larger **living space** and that rooms per person will increase. We assume the largest increase of rooms per person – in Hungary with 0.4 rooms/person for flats, and in Lithuania with 0.3 rooms/person – will be in the whole EU. The market will also drive high annual investments in renovations, as a cost-effective means to reduce emissions and enable climate neutrality.

[17] "Energy efficiency of large electrical appliances continues to improve rapidly. However this effect does not counterbalance anymore the rapid growth of the consumption of small appliances." https://www.odyssee-mure.eu/publications/efficiency-by-sector/households/electricity-consumption-dwelling.html

[18] Data from European Environmental Agency (EEA), Electric cars registered in the EU-27, Iceland, Norway and the United Kingdom, https://www.eea.europa.eu/data-and-maps/indicators/proportion-of-vehicle-fleet-meeting-5/assessment

The **electricity consumption of lighting and appliances** will decrease as the current trend in the People-powered storylines. In contrast, in the Market-driven storyline, we assume that number of appliances and use cases outweigh energy-efficiency savings in electricity consumption and remain at the current trend. In the Government-driven storyline we see an exponential decrease in line to meet the 2030 targets

In the **mobility sector**, car use will be largely reduced only in the People-powered scenario, as citizens switch to other and shared modes of transportation. The remaining car-fleet will be fully electrified by 2040. The Market-based storyline will trigger investments in electric cars, assuming a relatively stable overall use of cars. In line with the 'Fit for 55' package, there are no new fuel-based cars from 2035 onwards. There is little emphasis on public and communal solutions: Public transport is hardly expanded. In the market-directed storylines, transport systems change only moderately. Public transport is expanded, but the number of cars on the street decrease only slightly. However, fuel-based car engines will be faced out by 2030 – as done by some countries.

3 Linking QTDIAN and energy demand and system models

The modelling toolbox QTDIAN will be soft-linked to the energy system model Euro-Calliope and the energy demand models DESSTINEE, HEB and DREEM. We implement this linking to integrated empirical based development of social and political aspects of the energy transition into the model, and thus, to be able to perform a more realistic analysis of energy system trajectories. Figure 2 provides an overview of the intended linking efforts.

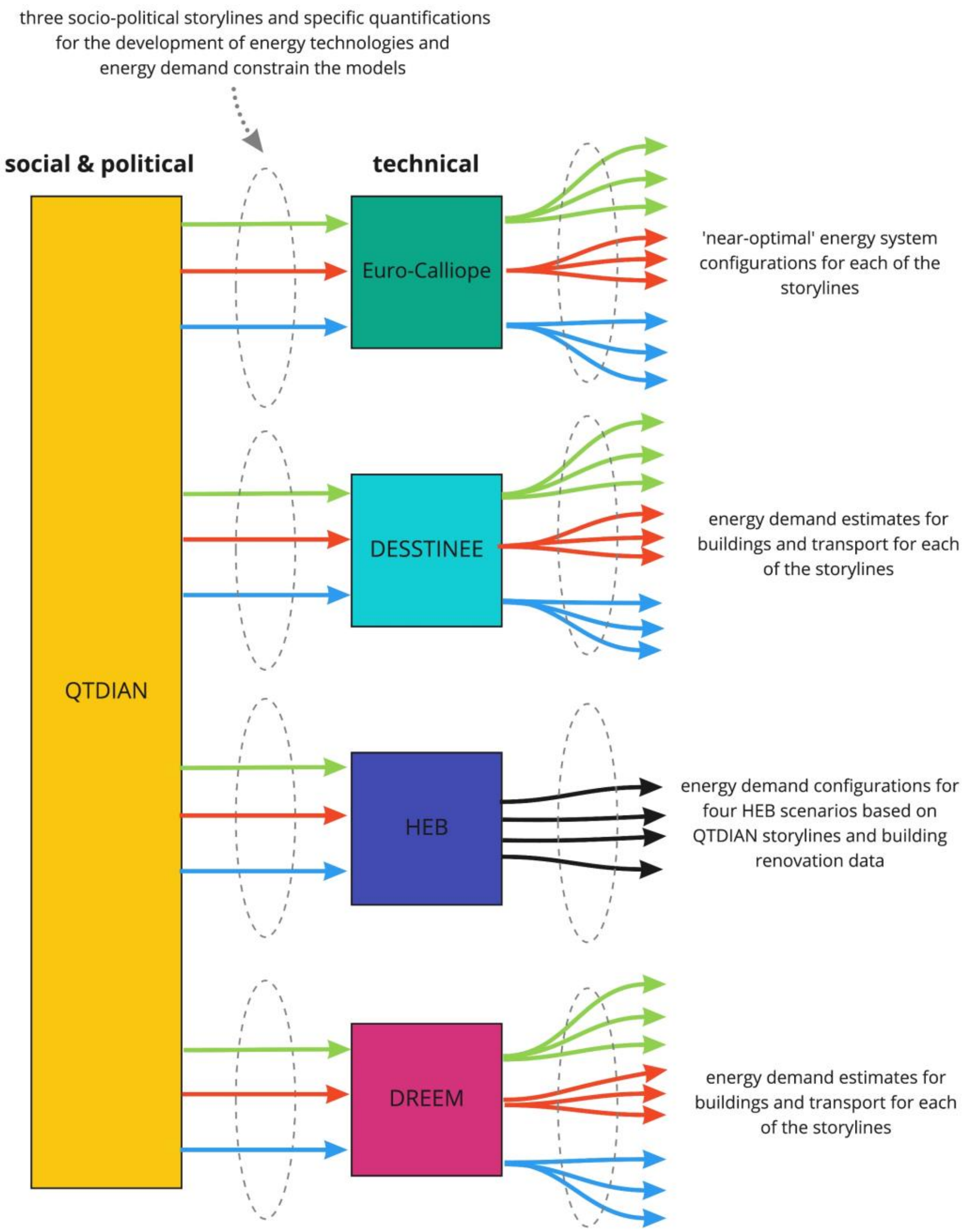

Figure 2: Intended model linkages between QTDIAN and Euro-Calliope, DESSTINEE, HEB and DREEM.

3.1 Linking QTDIAN and Euro-Calliope

3.1.1 Description of Euro-Calliope

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 levelised cost of power-to-methane in Europe (Morgenthaler et al., 2020); the impact of replacing cooking technologies in Italy (Lombardi et al., 2019); and the optimal spatial allocation of renewable energy in Italy (Lombardi et al., 2020) and Europe, using the Euro-Calliope model (Tröndle, 2020; Tröndle et al., 2020). The Euro-Calliope model used in this study is based on version 0.6.8 of the Calliope framework. It models the greenfield deployment of components of the energy system at a sub-national level, in 98 regions across 35 countries in Europe, as a linear programming problem. Its objective function is to minimise total system costs. The model is set up at hourly resolution for a full year, and it deploys technologies overnight to fulfil hourly demand in each modelled region.

Like all energy system models, Euro-Calliope is built on a set of assumptions that are driven by the modelling team (Ellenbeck and Lilliestam, 2019). These often reflect the latest literature from a techno-economic perspective as well as a prevailing view from the energy modelling community on the viability of certain technologies (for instance, CSP has lost policy support in Europe, even if it is a technically viable technology (Lilliestam et al., 2021)). To better ground the main model assumptions, and to constrain otherwise free variables to reasonable ranges, we believe it is pertinent to incorporate rigorously researched social-political storylines from the very beginning. This ensures that the Euro-Calliope model and its results represent future energy pathways that are aligned with broader, observed social realities.

3.1.2 Method to link QTDIAN with Calliope

Figure 2 shows how linking QTDIAN and Calliope would shape our understanding of future pathways between an understanding of social storylines, both qualitative and quantitative. First, quantitative data for three social storylines will be taken from QTDIAN, to be used to constrain the Euro-Calliope energy system model. Second, Euro-Calliope will be used to model end-state fully decarbonised energy systems for Europe for each storyline for 2050 (and an intermediate, partially decarbonised step for 2030). Rather than produce one 'cost-optimal' energy system configuration, several technically feasible configurations within 10% of the least-cost solution will be produced. This ensures that model artefacts don't heavily skew the results. For instance, a 1% better wind productivity in region A compared to region B would lead to region A always having the most possible wind deployment and region B none, even when the difference in productivity is well within the bounds of input uncertainties. These near-optimal energy system configurations can be filtered for downstream analysis based on qualitative components of QTDIAN's storylines, to select a subset of feasible energy system configurations that best represent each storyline.

To implement the QTDIAN quantitative storyline components defined in **Table 3**, we implement the following constraints in Euro-Calliope (including pseudo-mathematical equations describing constraints):

1. A maximum limit on total annual CO_2 emissions compared to 1990 levels. This is only pertinent for the 2030 model year, since the 2050 year is assumed to be fully decarbonised.

   Sum(emissions[carrier, region, hour] for all *carrier* in fossil_fuel_energy_carriers, region in model_regions, *hour* in year) <= energy_sector_emissions[1990] * emissions_reduction_target

2. A minimum contribution from renewable technologies to total consumption of electricity. As with (1), this predominantly impacts 2030, since Euro-Calliope does not represent carbon capture and storage (CCS). However, nuclear power is available.

   Sum(electricity_production[*tech*, *region*, *hour*] for all *tech* in [onshore wind, offshore wind, PV, hydropower, biofuel], *region* in model_regions, *hour* in year) / sum(electricity_consumption[*region*, *hour*] for all *region* in model_regions, *hour* in year) >= renewables_contribution_target

3. Energy intensity reduction will be applied to scale input end-use demands across all sectors. This implies that reduction in energy intensity does not change the profile of demand within a year.

4. Fossil fuel phase-out. As with (1) and (2) this is only pertinent for the 2030 model year, since the 2050 year is assumed to be fully decarbonised. In 2030, coal plants will not be available in the people-powered storyline model, will be capped based on expected total phase-out by 2038 in the government-directed storyline, and will be capped based on current capacity in the market-driven storyline.

5. A limit of cross-border international NTC will be based on the hourly absolute net import/export in a country compared to total electricity production in that country.

   Abs(electricity_import[*region*, *hour*] - electricity_export[*region*, *hour*]) <= sum(electricity_production[*tech*, *region*, *hour*] for all *tech* in electricity_production_techs) * percentage_NTC_limit for all *region* in model_regions, *hour* in year

6. Car use reduction will be applied to total demand for passenger vehicle travel in the input data. The percentage of electric vehicles in the vehicle fleet in 2030/2050 will be applied as a fixed percentage of total vehicle travel that needs to be met by either fuel-driven vehicles (ICE) or electric vehicles (EV).

   Sum(mobility_production [EV, *region*, *hour*] for all *hour* in year) == Sum(mobility_production[*tech*, *region*, *hour*] for all *tech* in [EV, ICE], *hour* in year) * share_of_EVs_in_fleet for all *region* in model_regions

7. The preferred electricity mix will be imposed by set shares of specific renewables in the electricity mix as well as strict limits on total capacity of certain renewables. In the people-powered storyline, technologies which allow for a high share of citizen participation, meaning rooftop solar

PV and onshore wind are prioritised. Consequently, all available rooftop space will be assumed in use, as well as all available space for onshore wind. Open-field PV and offshore wind will consequently be added in the optimisation only in situations in which the other technologies are insufficient to meet demand. In the government-directed storyline, a balanced mix of renewables is desired, which will be enforced by fixed, even shares of each renewable technology in the mix. In the market-driven mix, technologies with the lowest costs will be given preference.

Sum(electricity_production[*specific_tech*, *region*, *hour*] for all *region* in model_regions, *hour* in year) <= Sum(electricity_production[*tech*, *region*, *hour*] for all *tech* in [onshore wind, offshore wind, PV, hydropower, biofuel], *region* in model_regions, *hour* in year) * renewables_contribution_target [*specific_tech*] for all specific_*tech* in [onshore wind, offshore wind, open field PV, rooftop PV]

8. Grid development will be based on ENTSO-E's TYNDP2020 scenario reference and expanded grids, assuming the expanded grid is relevant for the government-directed storyline and reference for the people-powered storyline. The market-driven storyline will use grid transfer capacities according to Euro-Calliope's internal dataset as a lower bound, with the ability to pay for increased capacity on those lines.

9. Grid-scale battery projects will be enforced by the minimum storage capacity of batteries in Europe as a whole. We do not differentiate between grid-scale and home batteries in Euro-Calliope, but the cost of batteries will be changed in each storyline to reflect the dominant battery choice in each (people-powered: home batteries, government-directed: average of grid scale and home, market-driven: cheapest).

   Sum(battery_storage_capacity[*region*] for all *region* in model_regions) >= expected_projects_storage_capacity

10. Onshore wind power limits cannot be imposed by distance to housing as the available datasets describing urban settlements are not of sufficient quality to undertake this task. However, a limit on land that can be developed for onshore wind deployment can.

    wind_land_use [*region*] <= maximum_land_use_percentage * land_area[*region*] for all *region* in model_regions

3.1.3 Linkage challenges

Not all elements of the storylines given in **Table 1** can be incorporated into Euro-Calliope. This is due to the difficulty in quantifying all aspects of storylines and the available locations in the Euro-Calliope dataset and model workflow in which quantifications can be included. For instance, the minimum distance of turbines from dwellings requires a high-resolution spatial dwelling database for the European continent, which is not available. Those storyline elements included for incorporation in Euro-Calliope reflect what can be included with presently available data; in future model runs, should further data become available, additional QTIDIAN parameters can be included.

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

Conversely, Euro-Calliope offers many more areas for constraints to be added that cannot be provided by QTDIAN at present. For instance, Euro-Calliope is represented at a high spatial resolution, but storyline outputs are limited to totals and averages across Europe as whole. Similarly, most constraints provided by QTDIAN are annually aggregated and thus cannot capitalise on the sub-daily temporal resolution offered by Euro-Calliope. Finally, not all end-use energy sectors can be specifically constrained by the storylines. Space heat and hot water demand in buildings, fuel requirements in aviation, shipping, and industry processes can all be influenced by a change in systemwide 'energy intensity' (point 3. above) but not by targeted constraints.

Of those constraints that can be included, there is no particular challenge since the Calliope energy modelling framework is sufficiently generalised to enable the defined constraints to be applied without edits to the software itself.

3.2 Linking QTDIAN and demand models

Long-term changes in the energy system are largely shaped by several socio-political factors, such as lifestyles and policies for energy-related appliances and renovations, and these factors impact both demand and supply (Cherp et al., 2018). Therefore, including socio-political factors into the SENTINEL demand models is essential to provide realistic future demand scenarios in the context of EU climate neutrality. Therefore, in SENTINEL, the individual demand models are soft linked with QTDIAN to include the socio-political aspects of the energy transition.

Soft-linking demand models with QTDIAN is a complex task as it requires the identification and quantification of different socio-political storylines that can be used directly as input by the demand models. Thus, after examining each of the demand model's input and output data requirements along with their assumptions, we have identified six key parameters of the QTDIAN toolbox that can be used by the demand models. The magnitude of the six parameters namely, renovation rate, the share of advanced buildings within new and renovated buildings, energy consumption for appliances, electric vehicles and travelled distances, vary across three different storylines of QTDIAN in order to reflect different socio-political scenarios. Therefore, by using these parameters as input in the demand models, the demand models produce more realistic future demand scenarios in the context of EU climate neutrality. **Figure 3** below summarises the soft-linking approach.

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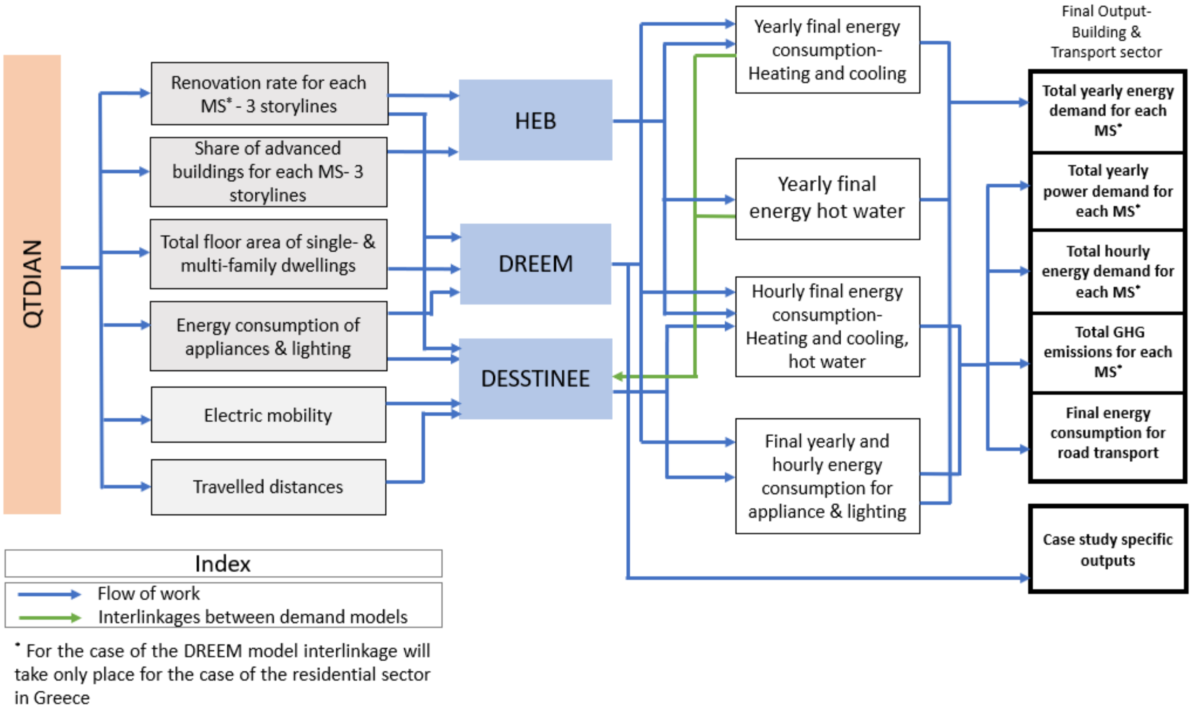

Figure 3: Linking QTDIAN as input for the three energy demand models.

3.2.1 Linking QTDIAN and DESSTINEE

3.2.1.1 Description of DESSTINEE

DESSTINEE is an open-source model developed at Imperial College London. It investigates the effects of demographic, economic, and technological changes on future final energy demand and power supply, both at yearly and hourly dimension. It has a country level geographical resolution, which can easily be expanded to cover sub-regions within a country. DESSTINEE has been used for simulating load curves under different decarbonisation scenarios, for example "two degree target scenarios" in the United Kingdom and Germany (Boßmann and Staffell, 2015).

DESSTINEE is programmed in VBA with a user-friendly interface in Excel. It is constituted by 3 modules. Module 1 forecasts annual final energy consumption, accounting for 11 energy carriers, using sectorial partial decomposition for service demand. The latter is projected based on user defined population and GDP growth rates, efficiency improvements, and fuel switching towards electric heat and transport. In the context of the SENTINEL project, this module has been employed with the purpose of defining technology incorporation and fuel baskets for final energy uses, compatible with climate neutrality by 2050 and newly announced decarbonisation targets by 2030 (Oreggioni G D, in preparation). For key final energy uses, annual figures for power usage are hourly distributed (Module 2), having the resulting power demand profiles been validated for all countries in Europe by crosschecking against official data for hourly system load.

Hourly power demand profiles can be used as input for the DESSTINEE's Supply Module (Module 3) – allowing the simulation of the hourly operation of the power systems – by accounting for: user provided generation potential for intermittent renewable sources; assumptions for transboundary transmission capacity; and efficiency and installed capacity figures for thermal generation plants. The model establishes a power matrix aimed at minimising running cost. Both for demand and supply, DESSTINEE reports fuel usage and fossil CO_2 emissions, and we are currently extending the model to also quantify other greenhouse gas emissions.

Forecasting service demand and final energy consumption relies on inputs and assumptions regarding behavioural changes, particularly, in terms of building occupancy, evolution for building surface area, thermal comfort patterns, and modal shifts for transport. Having access to detailed, and systemically obtained information in this domain will improve the accuracy and especially the policy relevance of the results as they will be closer connected to actual developments and pending political decisions. Linking DESSTINEE's inputs with QTDIAN outputs (and storylines) could significantly contribute to this.

3.2.1.2 Method to link QTDIAN with DESSTINEE

As part of the interlinking work, outputs from QTDIAN are included in the simulation of the 2050 climate-neutrality scenario in DESSTINEE, employing the indicators presented in **Table 4**. Especially, we include:

1. Trends and projections for building renovation, for each QTDIAN storyline, will be used for estimating the improvement rates in building envelope efficiency. Currently, this value in DESSTINEE is nationally updated – considering building age profiles- and data from EU wide scenarios (European Commission, 2020, 2018). Input from QTDIAN will be used for defining a future age profile for buildings, which will be supplemented with assumptions on building energy performance and country-level statistics for building stocks.

2. The future evolution for country-level household surface is currently forecasted, in DESSTINEE, as function of trends for national GDP per capita. Inputs from QTDIAN will be considered for defining an EU wide increase ratio whilst the afore mentioned mathematical relationships will be used for disaggregating total continental household area by countries.

3. DESSTINEE uses an appliance index to compute for the increase of power consumption within residential buildings. This index includes the effects associated with the trends in the number of appliances per building and the possible efficiency increases. This coefficient is, in DESSTINEE, currently based on projections for power usage for appliances – from EU wide scenarios- (European Commission, 2020, 2018) and country-level functions that correlate power consumption with GDP per capita. The figures provided by QTDIAN, at continental level, will be considered to replace the data from the afore mentioned EU scenarios.

4. National increases for the service demand associated with passenger cars, in DESSTINEE, are based on the forecasts presented in the 2016's EU Reference Scenario (European Commission, 2016; Loulou and Labriet, 2008). These inputs will be replaced using the EU wide growth rate, informed by QTDIAN, whilst the data from the afore mentioned scenario will be accounted for allocating the total service demand among countries.

5. Future national fuel shares, within the passenger car fleet, are modelled in DESSTINEE based on: forecasts in continentally wide scenarios, econometric relationships for country-level electric car ownership; and present distribution of biofueled units among Member States. Inputs from QTDIAN will replace the assumptions for electrification and fossil fuel shares, obtained from EU wide scenarios, whilst the national allocation methodology currently used in DESSTINEE will be kept.

3.2.1.3 Linkage challenges and possible benefits

For the variables considered in Table 4, the integration between QTDIAN and DESSTINEE at continental level is quite straightforward. The main challenges are related to the downscaling of the EU defined targets into national circumstances. This could lead to estimates that could well define the whole EU27+UK bloc but that could be more uncertain at country level, both because national data is not always present and hence unknown, and because single policy decisions may have large effect on the national level, making the future more uncertain the deeper we zoom in. As indicated in 3.1.3, there are several final energy uses for which there are no constrains from QTDIAN such as the commercial sector or other passenger transport modes (rail, aviation and shipping). Since this is the first release of the model, this interlinkage exercise is a good starting point for future work – as further elaborated in the Discussion.

There are benefits of such an interlinkage, especially for the service demand quantification in heating in buildings and transport. In DESSTINEE, several aspects of service demand quantification account for the future evolution of income indicators. Updating such projections with figures that also consider possible behavioural changes is of great value – considering that some of these variables have a key societal component in terms of population and family dynamics, consumer preferences, and patterns for building refurbishing and mobility.

3.2.2 Linking QTDIAN and HEB

3.2.2.1 Description of HEB

HEB (High Efficiency Buildings) model was originally developed in 2012 to calculate energy demand and CO_2 emissions of the residential and tertiary building sector until 2050 under three different scenarios (Petrichenko, 2014; Urge-Vorsatz, 2012). HEB model calculates the energy demand in the four scenarios until 2060 based on the most recent data for macroeconomic indicators and technological development. This model is novel in its methodology as compared to earlier global energy analyses and reflects an emerging new paradigm: the performance-oriented approach to buildings energy analysis. The model takes a bottom-up approach, as it includes rather detailed technological information for the building sector, however, it also benefits from certain macroeconomic and sociodemographic data which include population, urbanisation rate, and floor area per capita. The four scenarios of HEB model are discussed below:

<u>Deep Efficiency Scenario:</u> Deep Efficiency Scenario demonstrates the state-of-the-art of construction and retrofit technologies that can substantially reduce the energy consumption of the building sector and hence, CO_2 emissions, while also providing full thermal comfort in buildings. This scenario includes exemplary building practices that have been implemented in the EU for both new and renovated buildings.

<u>Moderate Efficiency Scenario:</u> The scenario incorporates present policy initiatives particularly the implementation of the Energy Building Performance Directive (EPBD) in the EU and building codes for new buildings in other regions. The key assumptions of the moderate efficiency scenario are presented in the **Table 5**.

<u>Frozen Efficiency Scenario:</u> This scenario assumes that the energy performance of new and retrofit buildings do not improve as compared to the baseline and retrofit buildings consume around 10% less than standard existing buildings for space heating and cooling. Furthermore. most new buildings have a lower level of energy performance than in moderate scenario due to lower compliance with building codes.

<u>Towards Net-Zero Scenario:</u> The last scenario models the potential of deploying "Net Zero Energy Buildings" – buildings that can produce as much energy locally through the utilisation of renewables as they consume on an annual balance. It differs from the other three scenarios to the extent that it not only calculates the energy consumption but already incorporates the local energy supply to arrive at the final energy demand. In other aspects, it uses the same parameters as the Deep Efficiency Scenario.

The aim of the scenario analysis is to capture the importance of different policy acts on building energy efficiency measures and show how much the final energy consumption of the building sector can be reduced across the EU. **Fehler! Verweisquelle konnte nicht gefunden werden.** 1 summarises the actual parameters of the four scenarios.

Table 5: Parameters of the four HEB scenarios.

Parameter	Deep Efficiency Scenario	Moderate Efficiency Scenario	Frozen Efficiency Scenario	Towards Net Zero Scenario
Initial renovation rate	Country-specific data from the from IPSOS-Navigant report	Country-specific data from IPSOS-Navigant report	Country-specific data from the IPSOS-Navigant report	Country-specific data from the IPSOS-Navigant report
Accelerated renovation rate	Market-driven storyline renovation from QTDIAN after 2027	Government-directed storyline renovation data from QTDIAN after 2027	Country-specific data from the People-powered storylines from QTDIAN	Market-driven storyline from QTDIAN after 2027
Energy Efficiency measures of new buildings	New buildings are built to regional standards	New buildings are built to regional standards	New buildings do not improve as compared to the existing stock	New buildings are built to regional standards
Energy efficiency measures of renovated buildings	Renovations reduce the energy demand approximately by 30%	Renovations reduce the energy demand approximately by 30%	Renovations reduce the energy demand approximately by 10%	Renovations reduce the energy demand approximately by 30%
Share of advanced buildings within	All new and retrofitted buildings have very	70% of the new and retrofitted buildings have very	Advanced buildings are only introduced by the	All new and retrofitted buildings have net

New and retrofitted stock	low energy demand (advanced buildings) after 2027 in the EU	low energy demand (advanced buildings) after 2027	same share as present share of advance buildings	zero energy demand after 2027 in the EU.

Based on these four scenarios, the key outputs of the HEB model are floor area projection for different types of the residential and tertiary buildings in different regions and Member States, the total energy consumption of residential and tertiary buildings, energy consumption for heating and cooling, energy consumption for hot water energy, total CO_2 emission, CO_2 emission for heating and cooling, and CO_2 emission for hot water energy.

3.2.2.2 Method to link QTDIAN with HEB

Like most building demand model, the HEB model does not include socio-political indicators and hence, the scenarios of the HEB model may not be realistic enough to represent the future energy demand. Thus, by using QTDIAN storylines and the outcome of the storylines, HEB can include the socio-political aspect in each of the scenarios that make the scenarios much more realistic. Specifically, two of the key inputs used in HEB are building renovation rates, and share of advanced buildings for each of the EU MS. Both data vary across different scenarios and accordingly the final energy demand of the building sector is calculated for each of the scenarios.

1. Renovation rate: To better reflect the socio-political aspects in the HEB, we use the sum of medium and deep renovation rates for the initial renovation rate data from the IPSOS-Navigant report. The renovation data in QTDIAN varies as per storylines to reflect different socio-political scenarios, and by using the renovation data for each of the storylines, HEB scenarios include different socio-political storylines as well. For example, the renovation data for people-powered storyline is used as frozen efficiency renovation data in the HEB model. Similarly, the Government-directed and Market-driven storylines and data are used in the Moderate and Deep Efficiency Scenarios of the HEB model respectively. The renovation data reflects any type of retrofit that has a significant influence on the heating and cooling energy demand of the building.

2. Share of advanced buildings within new and renovated buildings: In the HEB model, scenario-specific assumptions are made on how much percentage of the renovated buildings are advanced (such as Net zero buildings, and passive houses) or non-advanced. These two categories reflect different energy efficiency levels where the non-advanced buildings are assumed to be the "business-as-usual", while advanced buildings are the technically possible best ones in terms of low energy consumption. Thus, for the Deep Efficiency and Towards net zero scenarios in the HEB model, we use the deep renovation data from the Market-driven storyline of QTDIAN from assuming the share of advanced buildings. Similarly, for the moderate efficiency scenario, we use the data from Government-directed storylines.

3.2.2.3 Linkage challenges and possible benefits

Any soft linking of the models faces certain challenges and linking QTDIAN and HEB is no exception either. The two major challenges while soft-linking these two models are the follows:

- In the QTDIAN input data from where the renovation rate is defined, the energy savings are expressed based on primary energy, while in HEB the specific energy use of buildings (consequently the savings too), as well as the output, is expressed in final energy. Thus, we have assumed in HEB that there is no significant difference between savings in final energy and primary energy regarding building end-uses.
- In the HEB model, we aim to decouple building-related energy consumption from onsite production (e.g. photovoltaics), therefore the reduction in energy demand through PV installation is not considered within the savings between existing and retrofitted buildings. At the same time, the input data from the Ipsos-Navigant report used by QTDIAN consider this option when calculating the energy savings of the renovations. To account for this issue, we only use the share the renovation data for different storylines and use our assumption on energy savings or energy performance for advanced and non-advanced building types.

Apart from these challenges, there are some usual challenges as well, for instance, data comparability between two models, comparing the underlying assumptions of these two models etc. However, we could encounter these challenges to exhaust the benefits of soft-linking these two models. The biggest benefit of soft-linking QTDIAN and HEB is having more representative and realistic scenarios in HEB. Thus, the demand data produced by HEB are much more accurate and closer to the reality that can be better applied in policymaking.

3.2.3 Linking QTDIAN and DREEM

3.2.3.1 Description of DREEM

The **D**ynamic high-**R**esolution d**E**mand-sid**E** **M**anagement (DREEM) model is a hybrid bottom-up model that combines key features of both statistical and engineering models. The model serves as an entry point in Demand-Side Management (DSM) modelling in the building sector, by expanding the computational capabilities of existing Building Energy System (BES) models by not only calculating energy demand but also assessing the benefits and limitations of demand-flexibility, primarily for consumers as well as for other power actors involved (Stavrakas and Flamos, 2020). The novelty of the DREEM model lies mainly in its modularity, as its structure is decomposed into individual modules characterised by the main principles of component-/ modular-based systems modelling approach, namely "the interdependence of decisions within modules; the independence of decisions between modules; and the hierarchical dependence of modules on components embodying standards and design rules" (Pereverza et al., 2019) (**Figure 4**). This modular approach allows for more flexibility in terms of possible system configurations and computational efficiency towards a wide range of scenarios, studying different aspects of end-use.

The modular structure of the DREEM model allows for a wide range of functionalities regarding different decarbonisation scenarios of the European building stock. Next to calculating energy demand, such scenarios could also enable the evaluation of the performance and replicability potential of conventional and innovative energy efficiency measures, in terms of their long-term energy savings, sustainability, risk, and return of investment. Such an evaluation would focus on assessing the potential benefits of each measure at a disaggregated (i.e., households-neighbourhood) level, and then allowing for upscaling at a national level. However, considering the role that the human factor is expected to play in these scenarios, it is important that socio-political aspects are incorporated into the model, to better ground model assumptions and to constrain otherwise free variables to reasonable ranges. In this regard, a synergy with QTDIAN allows for more accurate parameterisation of the model than otherwise. This could also ensure that the model and its results represent energy transition pathways that are aligned with broader social storylines.

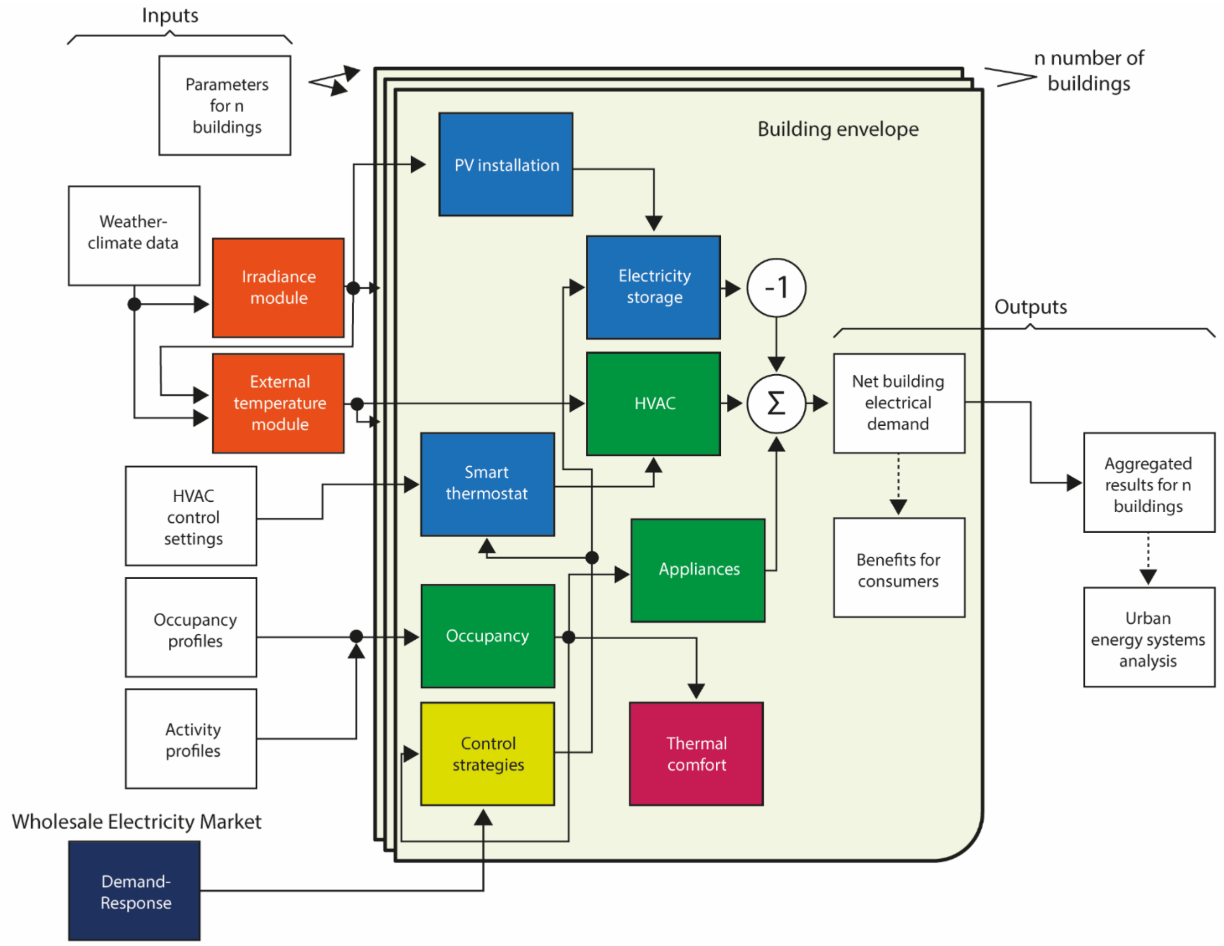

Figure 4: The DREEM model's architecture as it currently stands. Source: Stavrakas and Flamos, 2020.

3.2.3.2 Method to link QTDIAN with DREEM

Figure 3 shows how linking QTDIAN and DREEM would shape our understanding of energy transition pathways between an understanding of social storylines, both qualitative and quantitative. The main idea is that quantitative data for three social storylines will be taken from QTDIAN and will be used as inputs to parameterise the DREEM model. DREEM will be then used to model the energy transition for each storyline in the residential sector in Greece by 2050 for the different values of the storyline variables presented in Table 6. A different mix of energy efficiency measures (in terms of deep renovation) and technologies for heating and cooling (i.e., natural gas boilers, heat pumps, air-conditioning units) will be tested in accordance with the specifications of the transition scenarios presented by (Stavrakas et al., 2021). Indicative, final results will include final energy consumption per type of fuel, total energy savings due to renovation, total fuel savings due to renovation, tonnes of CO_2 avoided, economic benefits for households, etc. In addition, considering recent developments of energy and climate laws, DREEM will also quantify potential implications for households from the extension of the emission trading scheme (ETS) to the residential sector for different feasible values of the carbon price. Finally, results from DREEM will be filtered based on the qualitative components of QTDIAN's storylines to select a subset of feasible technological configurations that best represent each storyline.

Table 6: Storyline variables and quantifications for energy demand modelling with DREEM in the Greek residential sector.

Storyline variables & values	People-powered	Government-directed	Market-driven
Building renovation (residential, floor space)	Deep renovation rate of 0.2% annually; medium renovation of 1.1%	Deep renovation rate of 2.1% annually, 0.9% medium renovation	Deep renovate rate of 3% annually
Total floor area of single- & multi-family dwellings	Single: 160792.9 mm² (2016) Multi: 212390.53 mm² (2016)	Single: increase by 0.2% annually Multi: increase by 0.09% annually	Single: increase by 0.4% annually Multi: increase by 0.2% annually
Private electricity consumption of appliances and lighting	Linear decrease as of today	Exponential decrease to meet the 2030 target	Constant

3.2.2.3 Linkage challenges and possible benefits

Not all elements of the storylines given in **Table 4** can be incorporated into DREEM. This is due to the difficulty in quantifying all aspects of storylines and the model's structure, which doesn't allow for the inclusion of the storyline variable "Rooms per person." In addition, since the focus of the model is in the residential sector, the storyline variables "Electric vehicles" and "Travelled distances" can also not be incorporated. **Table 6** represents the storyline inputs that can be realistically used by the model and for which there is no particular challenge, since these variables are already model inputs. On the other hand, since DREEM allows for greater sophistication with the integration of complex dynamics of the building stock transformations into the modelling process, it provides the capability to adopt a more interdisciplinary approach, encompassing the inclusion of socioeconomic and demographic factors. This could lead to parameterisation areas that may not be provided by QTDIAN at present. For example, in the context of the modelling exercises described above, DREEM will explore aspects of energy poverty in the residential sector by considering particularities of energy poor households. In addition, DREEM can also be parameterised to reflect on the dependence of energy consumption to individual behaviour towards better-informed policymaking that motivates people to regulate their energy consumption as a way to benefit financially from obtaining energy saving practices. These are potential synergies with QTDIAN that need to be further investigated.

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

4 Discussion, outlook and conclusions

After the release of the QTDIAN modelling toolbox Version 1 (Süsser et al., 2021a), this interlinkage constitutes the first concrete work to integrate the QTDIAN outputs in energy demand and system models.

Linking QTDIAN with energy system and energy demand models allows for a better representation of the socio-political drivers and barriers for technology changes and climate change mitigation measures, contributing to understanding how peoples' preferences, market conditions and policy frameworks can influence and lead to different service demand growth rates, fuel baskets, efficiency improvement trajectories, designs of energy landscapes, among others. The output data from QTDIAN provide updated values or values for indicators for which no data were available. Thus, it reduces the extent to which modellers use their own assumptions to constrain a future energy system and offers a concrete way for social scientists to feed findings into models through a new interdisciplinary link that is generally underdeveloped or inexistant. QTDIAN storylines also ensure that modellers do not create technically feasible energy systems that are outside the realms of reality. Unlike other social-political storylines, the inclusion of QTDIAN's quantified variables enable direct application of storylines into the modelling process, rather than relying on modeller interpretation or only bringing social-political aspects when discussing model outputs. They are also different than most existing approaches, because they are linked to governance logics in the energy sector, and not to exogenous factors such as "conflict or cooperation in global policy" or a supposed economy-environment dichotomy (e.g. the old IPCC SRES scenarios). By integrating these social and political aspects, energy models can derive more accurate and more policy-relevant results and thus be of more use to inform pending decisions.

In its present state, QTDIAN provides significant information about social and political development at continental and partially national scales. Two key reasons exist for this: **1.** Not all aspects of the storylines could be quantified, and **2.** the models to which QTDIAN links in this deliverable are not able to capitalise on all QTDIAN outputs. First, certain social and behavioural aspects, such as people's attitudes and lifestyles, can hardly if not impossibly expressed in numbers. If social scientific data are available, then often for a specific country or region and rarely for all countries in Europe, and they are often not available as panel data to account for changes over times. A better availability of survey data on social and political aspects of the energy transition could substantially improve modelling efforts, as could the availability of data on regulations, which is currently very difficult to obtain for more than single countries and years. Second, the models are often not formulated in a way that technology preferences and behavioural changes can be inherently included. For example, as a linear programming problem, Euro-Calliope cannot explicitly define merit-order assumptions on technology deployment (e.g., 'rooftop PV is always chosen in preference to open-field PV', etc.). Other energy system models may be better placed to include these aspects of QTDIAN. In addition, by modelling fixed years (e.g., 2030, 2040, 2050), the three supply/ demand models to which QTDIAN links here are unable to capitalise on aspects of storylines that set limits through time (e.g., maximum annual deployment rates, etc.), or deadlines that occur in years that are not modelled (e.g., phase-out of a technology by 2034, etc.). Furthermore, different challenges emerged by integrating different QTDIAN outputs, regarding data comparability and data availability (temporal and spatial scales).

We identified further demands for assumptions and data, which cannot be met by the current QTDIAN version. Being able to have a higher geographical level of detail, country or group of countries, would be beneficial for QTDIAN and for the energy demand and supply models within the SENTINEL consortium, which estimates rely on behavioural and societal changes. Furthermore, there are final energy uses not covered by QTDIAN, but for which behavioural aspects are also important – such as passenger rail, aviation, and navigation – when focussing on individuals. Empirical data are needed for the evolution of the travelled distance and possible trends in modal shifts. Another step forward in QTDIAN development could be to incorporate variables related to the preferences of the business sector, which will influence energy consumption for commercial buildings, industries, and freight transport.

In this deliverable, we presented the conceptual linkages between QTDIAN and Euro-Calliope, QTDIAN and HEB, QTDIAN and DESSTINEE, and QTDIAN and DREEM. In a next step, we will run the energy system and energy demand models with the integrated interlinkage with QTDIAN to evaluate the outcomes and added value of the interlinkage. This will be done in the context of the SENTINEL case studies. We are specifically interested in the changes in the modelling results due to the integration of social and political aspects in the models, and to understand what input parameters have the highest impact on the observed changes. Furthermore, new demands for QTDIAN emerged in the linkage process, which could be partially already met via updated data sets. In a next step, we will update the QTDIAN data set.

We conclude that linking the QTDIAN modelling toolbox with energy demand and system models has contributed to a more decision-relevant modelling approach that takes social and political aspects of the energy transition better into account. The intended updates regarding estimates for buildings and transport in the demand module would also substantially improve the modelling approach of the system models. As a result, the SENTINEL modelling framework will provide a set of more realistic pathways to achieve climate neutrality in the EU by 2050.

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