D7.1|A working paper detailing the model development

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Author(s): Stijn Van Hummelen, Jon Stenning, Sachin A. Babbar (CE) and Laszlo Szabo, András Mezősi, Mária Bartek-Lesi (REKK)

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Quality review: Emilie Magdalinski, Thomas Pellerin-Carlin (JDI), Stefano Proietti (ISINNOVA)

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Coordinators: Silvia Gaggi and Stefano Proietti (ISINNOVA)
E-mail: sgaggi@isinnova.org
sproietti@isinnova.org

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The project in brief

The Energy Union Framework Strategy laid out on 25 February 2015 aims at fostering a cost-efficient energy transition able to deliver secure, sustainable and affordable energy to all European consumers. It has embraced a citizen-oriented energy transition based on a low-carbon transformation of the energy system. At the end of the day, the successful implementation of the Energy Union will materialise in a change in energy production and energy consumption choices. Such choices are heavily shaped by particular economic prerequisites, value systems, gender-based preferences, efficiency of governance and the maturity of civil society.

The ENABLE.EU project attempts to understand the key drivers of individual and collective energy choices, including in the shift to prosumption (when energy consumers start to become also energy producers). The project will develop participatory-driven scenarios for the development of energy choices until 2050 by including the findings from the comparative sociological research. As differences between European countries remain salient, ENABLE.EU will have a strong comparative component.

The final aim of this project is to contribute to more enlightened, evidence-based policy decisions, to make it easier to find the right incentives to reach the twin goals of successful implementation of the Energy Union and Europe's transition towards a decarbonised energy system. To reach this final aim, ENABLE.EU will seek to provide an excellent understanding of the social and economic drivers of individual and collective energy choices with a focus on understanding changes in energy choice patterns. Results will be disseminated to relevant national and EU-level actors as well as to the research community and a wider public.

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1 Introduction

The Energy Union Framework Strategy aims to deliver a citizen-oriented energy transition based on a low-carbon transformation of the energy system. The successful implementation of the Energy Union will lead to a change in energy production and energy consumption choices. Such choices are heavily shaped by particular economic fundamentals, value systems, gender-based preferences, efficiency of governance and the maturity of civil society.

The ENABLE.EU project attempts to understand the key economic, socio-cultural, demographic and behavioural drivers of individual and collective energy choices. It aims to do this by:

- Identifying the key factors of energy choices in three areas: transport, heating & cooling, and electricity;
- Better grasping the interactions between individual and collective energy choices and the regulatory, technological and investment prerequisites of the Energy Union transition pillar;
- Looking at the social acceptability of energy transitions using a participatory foresight and assessment process engaging key stakeholders and selected households;
- Increasing the knowledge of governance and social mobilisation practices that encourage collective energy choices in line with the Energy Union objectives;
- Providing strategic policy recommendations to increase the social acceptability of energy transitions.

A key expected outcome of ENABLE.EU are policy scenarios based on contributions delivered in participatory foresight exercises and assessed using quantitative modelling, to compare the outcomes with the current long-term energy targets as part of the Energy Union and deliver policy. The present working paper focuses on the quantitative modelling that will be undertaken as part of the ENABLE.EU project. It presents the suite of models that are being applied in the modelling framework and the developments that are being made to them as part of ENABLE.EU.

ENABLE.EU's empirical approach complements existing theories and findings in the research to date and approaches the question of what drives energy choices through the lens of several energy services and activities, namely electricity consumption, mobility, heating & cooling, and prosumers. For each of these areas, other Work Packages provide new and useful insights on drivers and trends in energy consumption that Cambridge Econometrics and REKK can work with in order to further develop some of their existing modelling tools and ultimately inform the policy scenarios that will be assessed for the ENABLE.EU project.

The challenge for Cambridge Econometrics (CE) and REKK is therefore threefold:

1. To the extent possible, develop their models to better reflect the heterogeneity and complexity of decision-making processes, based on the research findings of the ENABLE.EU case studies;
2. Harmonise and link the models into a unique, comprehensive and dynamic modelling framework for the European Union, in order to be able to answer the main research questions of the project;
3. Translate the transition scenarios of Working Package 6 into quantifiable policy scenarios and assess these policy scenarios using the newly designed integrated modelling framework.

In total, 7 different models will be linked together for ENABLE.EU. To model the impact of changing household decisions regarding energy use, our modelling approach focuses in first instance on modelling the take up of specific technologies in each of the four case studies of the ENABLE.EU project (mobility, electricity consumption, heating & cooling, and prosumers). To do this we use a suite of technology diffusion models developed from the principles and data currently applied within E3ME (CE's macroeconomic model), which are themselves based upon FTT (Future Technology

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Transformations) models.

In diffusion models we can model what impact changes in decision-making by households can have on energy consumption. The take up of more energy efficient technologies by households leads to reductions in aggregate energy consumption, a reduction in greenhouse gas emissions, sectoral shifts and – depending on the prices of the technologies – changes in consumer spending. These impacts can be analysed in detail for all EU Member States by linking the diffusion models with CE's macroeconomic model E3ME.

The changes in energy consumption resulting from the diffusion of advanced technologies and their associated economic impacts will also affect demand and supply of electricity and gas. The additional impact on the EU's electricity and gas markets will be modelled using REKK's dispatch models - the European Electricity Market Model (EEMM) and European Gas Market Model (EEGM).

When linked together, the different diffusion models, macroeconomic model and dispatch models provide a unique modelling framework which allows us to assess many of the impacts changing household behaviour can have on the EU's economy and environment in the future.

While the model developments are ongoing, the purpose of this working paper is first and foremost to report progress. Chapter 2 of this report briefly describes the diffusion, macroeconomic and dispatch models that will be used in Work Package 7. In Chapter 3 we explain how the models will be adjusted to reflect the findings and objectives of the ENABLE.EU project. Chapter 4 describes how the different models will be linked in order to model the impact of changes in household behaviour on electricity consumption, the economy and the electricity and gas markets in the European Union. Chapter 5 introduces the type of policies and research questions that we can address with the models as part of the scenario modelling.

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2 Model descriptions

This section provides a brief description and the important design features of each of the models that will be part of the macro modelling framework for ENABLE.EU. This includes 4 different technology diffusion models (to be implemented by CE) covering three of the four ENABLE.EU case studies, a global macroeconomic model (applied by CE) and two dispatch models (applied by REKK). Whereas in this section we focus on a general description of the models, the developments to these models for the ENABLE.EU project are described in Chapter 3.

2.1 Technology Diffusion Models

2.1.1 Residential Prosumer Model

The residential prosumer model simulates the take up of solar PV in European Member States, Iceland and Norway. The model was first developed as part of a study on Residential Prosumers in the European Energy Union[1].

The starting point for the model is the calculation of technical potential. The technical potential is the upper limit of solar PV that can be installed per country. In this calculation it is assumed that only homeowners (with or without mortgage) are able to invest in solar PV, renters do not enter the market because of split incentives– asymmetry between who pays and who benefits (i.e. benefits accrue to residents who pay the electricity bill, while the cost of installation would fall on owners). Based on the average size of dwellings[2] and number of households[3] from Eurostat an estimate for the total roof area is determined. A reduction factor is then applied to include only those households which are suitable for investment (e.g. have a south facing roof). The amount of suitable homes is assumed to be 40%, based on estimates from Parsons Brinkerhoff (2015) and Eiffert (2003). Next it is assumed 0.13kW of solar capacity can be installed on $1m^2$ of suitable roof area[4]. The calculation of total technical potential is done for each country.

The cost-effectiveness distribution curve takes into account the financial benefits and costs from solar PV installations. These costs are spread over the lifetime of the solar PV. In order to determine today's value, i.e. the net present value (NPV), these benefits and costs are discounted using the market interest rate. The market interest rate is the rate at which households can borrow money against their mortgage (to reflect the probable decision environment of an investment by a household). The net present value is the net present benefit minus the net present cost. The net present benefit is defined by the discounted future revenue from the electricity bill savings, Feed-in-Tariff income and net metering income. The net present cost is the CAPEX cost, discounted OPEX costs, grid fees and taxes. The NPV is calculated for the mean household in each country in each year up to 2050.

$$NPV \ = NPV\ Export\ Income + NPV\ Electricity\ Bill\ Savings + NPV\ Other\ Subsidies - NPV\ Costs$$

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[1] Gfk, Milieu Ltd, Cambridge Econometrics Ltd, Helion Research and COWI A/S, CentERdata (2017), "Study on Residential Prosumers in the European Energy Union". European Commission, Directorate-General for Justice and Consumers. Accessed on 25/09/18 at: https://ec.europa.eu/commission/sites/beta-political/files/study-residential-prosumers-energy-union_en.pdf

[2] Eurostat (2017), data code: ilc_hcmh01

[3] Eurostat (2017), data code: lfst_hhnhtych

[4] Energy Saving Trust (2015), 'Solar Energy Calculator Sizing Guide'. The 'average detached house', with roof area of 29.5m2 would have space for 18 panels, with total capacity of 4kW; the 'average semi-detached house' with roof area of 20m2 would have space for 12 panels (and total capacity of 2.6kW).

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Further information and a detailed description of the equation can be found in Chapter 9 of the original report[5].

To carry out the calculation for the NPV a number of assumptions are made, based on the most recent data available for each country:

- the mean size of installations (in kWp)
- mean CAPEX and OPEX costs
- the policy support mechanism and available subsidies
- current and future expected electricity prices
- market interest rates
- load factors

The available policies and subsidies are summarised in Table 2.1 below.

Policy type	Description
Feed-in-Tariffs	Prosumers are provided long-term contracts (usually of 10 to 25 years) by energy providers for electricity generated and exported to the grid. The Feed-in Tariff can be fixed, or designed to decrease as the technology matures. Prosumers pay the retail price for electricity they consume from the grid.
Feed-in Premiums	Feed-in premiums are long-term contracts that are designed to reduce short-term market exposure to elevated levels of grid-connected intermittent renewables. The payment for electricity exported to the grid is dependent on current wholesale market prices and so encourages electricity exports to the grid when it is needed, and self-consumption during periods of high electricity supply. The premium can be fixed or sliding (i.e. to reduce the gap between the wholesale price and the Feed-in Tariff).
Net-metering	Surplus electricity is fed back into the grid and prosumers are only charged for the net difference between electricity consumed from the grid and that fed back into the grid. The netting period (over which net bills are calculated) can be up to one year in length. Prosumers effectively use the grid for electricity storage and so there is no additional benefit of self-consumption versus exporting electricity to the grid, particularly if there is a long netting period.
Capital subsidies and loans	Subsidies or loans are provided to cover the costs of materials and/or installation. In some cases, prosumers are also eligible for reduced rates of VAT on solar PV equipment.

Table 2.1: Key policies modelled

Figure 2.1 below is an example of the cost-effectiveness distribution curve. The area under the curve represents the technical potential for residential solar PV installations. The mean household in this example receives a net present value of investment at €7,000. The left-hand tail of the distribution curve represents those households who would receive less NPV from investment. This may represent limited subsidy support or high CAPEX cost of investment in that country.

[5] Gfk, Milieu Ltd, Cambridge Econometrics Ltd, Helion Research and COWI A/S, CentERdata (2017), "Study on Residential Prosumers in the European Energy Union". European Commission, Directorate-General for Justice and Consumers. Accessed on 25/09/18 at: https://ec.europa.eu/commission/sites/beta-political/files/study-residential-prosumers-energy-union_en.pdf

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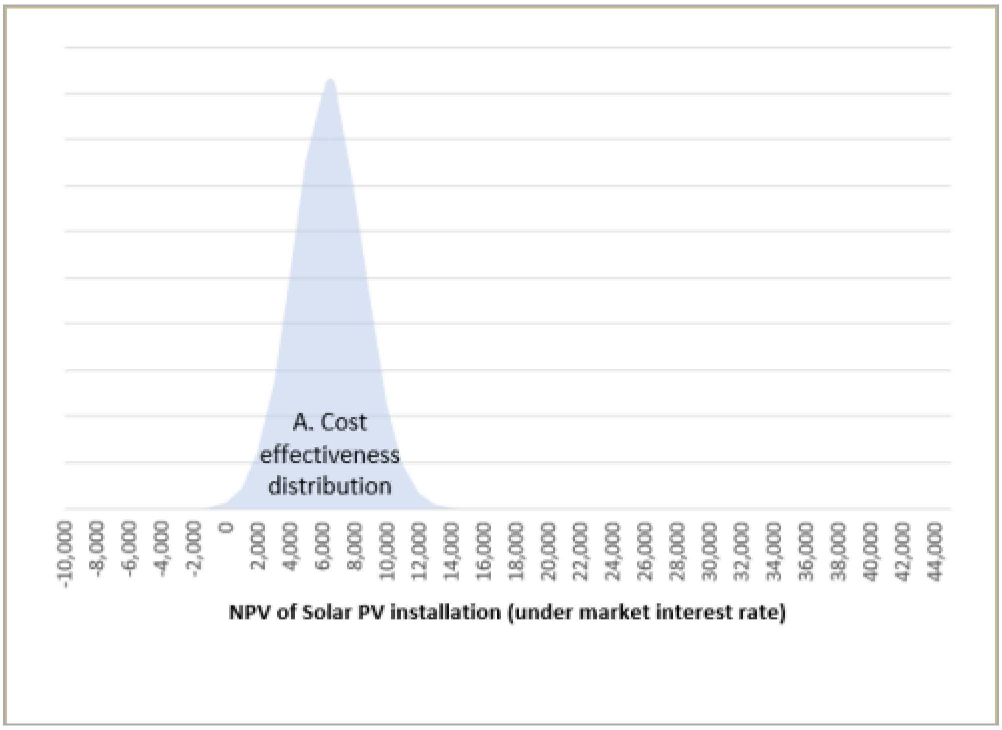

Figure 2.1: Example of cost-effectiveness distribution curve

Whilst the financial element is an important part of the investment decision it is not the only aspect. There are also non-financial barriers which reduce the attractiveness of investment. This is captured by the consumer preference curve. A review of the literature on the willingness to pay and required rate of return on solar PV investments was carried out to help determine this distribution curve. The current mean required rate of return is estimated to be 6.2% based on reports from Parson Brinkerhoff (2015) and NERA (2015). The required rate of return encompasses more than the discount rate (i.e. the individual's time preference), it also incorporates other preferences they may have (e.g. the administrative burden of investment). Figure 2.2 shows an example of the consumer preference distribution curve, showing that the mean consumer will only invest in solar PV if the NPV is equal to €20,000. Those households in the left-hand tail are incentivised by a lower NPV, so are more likely to invest. This might be because they care more about producing their own energy, or the administrative burden is much lower. The opposite is true for households at the right-hand tail; households who are located here may have higher barriers to investment (e.g. do not like the aesthetics of solar PV, attribute a higher cost to the inconvenience and hassle of arranging for solar PV to be installed or lack the required information). These individuals are much less attracted to solar PV investment therefore they need to be compensated more, in this case a NPV of €34,000 to €36,000.

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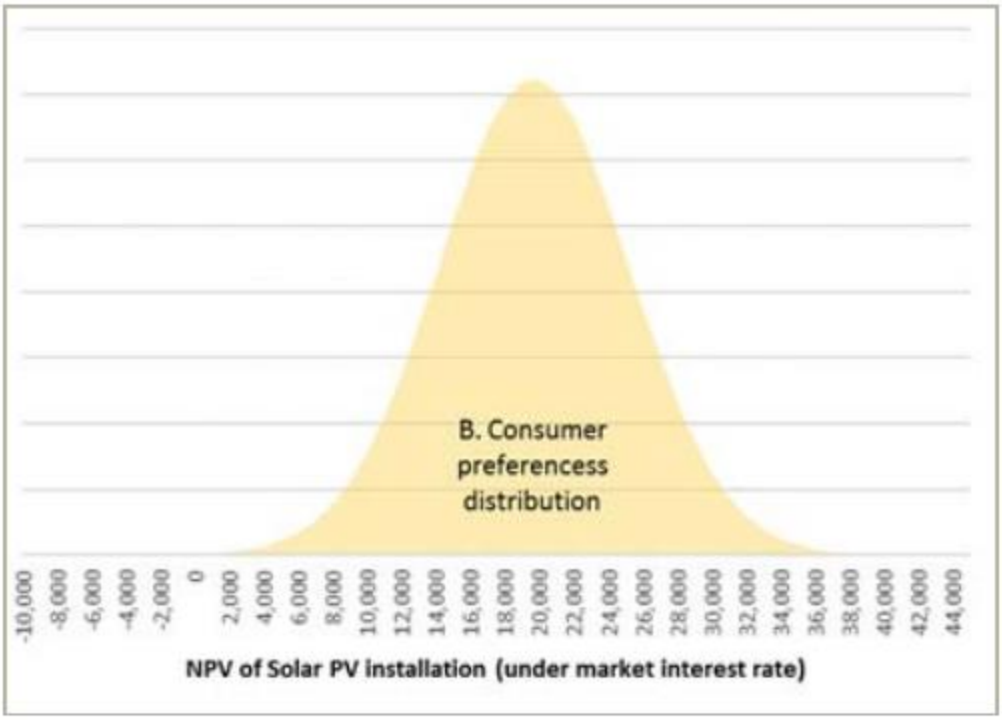

Figure 2.2: Example of consumer preference distribution curve

The residential prosumer model then combines these two curves to determine the rate of solar PV take up in a given country. Figure 2.3 illustrates that the area under both curves (C) represents the proportion of investments that take place in a specific country and year. Over time, costs and consumer preferences shift; if conditions are favourable (e.g. CAPEX cost fall) there will be a greater overlap of the two distribution curves and thus a higher diffusion of solar PV.

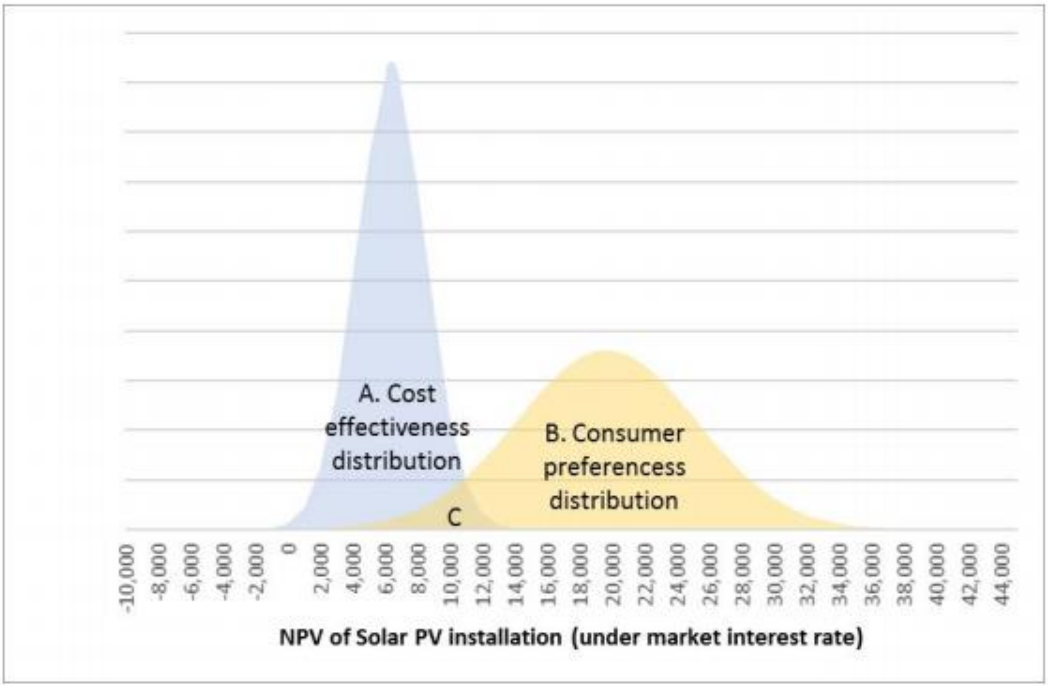

Figure 2.3: Combining cost-effectiveness and consumer preference distribution curve

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The residential prosumer model is calibrated to improve the estimation of the observed historical data. Unobserved factors for which there is no available data mean that it is not always possible for the model to reproduce historical data. To calibrate the model and better account for these unobservables in the future, a calibration factor is set equal to the difference between the share of solar PV investments that take place (observed data) and share of investment that are considered attractive (model calculations) over history.

In the baseline several key modelling assumptions are made:

- current policy measures are assumed to remain unchanged over the projection period used to calculate mean CAPEX and OPEX costs
- financial and non-financial consumer preferences, proxied by expected return on investment, are assumed to remain unchanged over the projection period
- the cost of equipment and installation (CAPEX costs) is assumed to fall by 1.4% pa
- the cost of maintenance (OPEX costs) is assumed to fall by 0.2% pa
- electricity prices for each EU Member State are set to grow in line with projections from the PRIMES reference scenario (although as shown in Chapter 4 these are over-written with prices from E3ME in later model runs)
- a 0.1% pa degradation rate is assumed for solar panels

The details of how these are defined for each member state, over the projected period is covered in Section 5.1.8 of the original report (Gfk, 2017).

The residential prosumer model calculates the take up of solar PV in each Member State in each year to 2050. The take up of solar PV is expressed in solar PV capacity (MW); both the cumulative and annual installation capacity is reported. The model also reports the proportion of technical potential capacity that is modelled to be taken up and the number of households that are prosumers, as well as the payback period for the mean household in years.

2.1.2 Future Technology Transformation Models

Future Technology Transformation Models (FTT) are diffusion models that specifically model the decision-making process of investors/consumers wanting to invest in new technology but face a number of different decisions and constraints. This makes them very suitable for the ENABLE.EU project.

To estimate choices of micro behaviour for the mobility and heating case studies two separate models will be used; FTT:Transport and FTT:Heat respectively. The common approach of the FTT:Heat and FTT:Transport models can be defined by the same “evolutionary economic approach and the replicator dynamic equation” as in previous work for the power sector, FTT:Power (Mercure, 2012). FTT:Power estimates technology choices in the power generation industry, while FTT:Transport and FTT:Heat estimate the diffusion of technologies in other specific sectors of the economy (transport and heating) using similar methods. All of these models are fully integrated into E3ME, however for the purpose of this project FTT:Heat and FTT:Transport have been split out so necessary developments can be made. FTT:Power will remain integrated within E3ME.

All the FTT models have similar design features which are summarised through the explanation of FTT:Power (see next Section). In subsequent sections, the similarities and differences between the different FTT models are explained.

2.1.2.1 FTT: POWER

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A consumer and industry shift to renewable technologies for heating homes and fuelling transportation will cause a switch in the fuels used in the economy. Investors will need to make decisions about which power generating technology they will invest in to meet the increasing demand for electricity and changing prices. FTT:Power models the complex dynamics of investor decisions within the power sector.

FTT:Power uses a novel framework for the dynamic selection and diffusion of energy technologies. It was initially developed by J.-F. Mercure (Mercure, 2012) and has subsequently been integrated into E3ME. It uses a decision-making core for investors in electrical capacity, facing different technology options. The resulting diffusion of competing technologies is constrained by a global database of renewable and non-renewable resources (Mercure & Salas, 2012, 2013). The decision-making core takes place by pairwise levelised cost (LCOE)[6] comparisons, conceptually equivalent to a binary logit model, parameterised by measured technology cost distributions. This distribution curve captures the variation in costs for a single technology and therefore implies heterogeneity amongst the investors. The right-hand of the tail represents investors who face a high cost of technology (e.g. the location of a power plant may increase the cost of grid integration, or perhaps decisional issues that can occur in the work place). Costs include reductions originating from learning curves, as well as increasing marginal costs of renewable natural resources (for renewable technologies) using cost-supply curves. The diffusion of technology follows a set of coupled non-linear differential equations, sometimes called ‘Lotka-Volterra’ or ‘replicator dynamics’, which represent the better ability of larger or well-established industries to capture the market, and the life expectancy of technologies. Due to learning-by-doing and increasing returns to adoption, it results in path-dependent technology scenarios that arise from electricity sector policies.

The decision-making core of FTT:Power represents the decisions investors make when responding to changes in local electricity demand. The investor can decide to keep the existing infrastructure or invest in a new technology. Investors do this by comparing the LCOE of one technology to another technology. The LCOE is represented by a distribution curve to demonstrate the difference in cost faced by investors across the country: land may be more expensive or the labour costs may be higher. The distribution curve captures this variation. It should be noted that this treatment means the model does not explicitly look at the price on a local level in detail, but by including a distribution curve these elements are captured at the aggregate level. Consider two technologies, i and j, with mean levelised cost C_i and C_j from the probability distribution $f_i(C,C_i)$ and $f_j(C,C_j)$. Investors compare the mean cost of each technology and decide to invest in the one with the lowest cost. Consider a situation where all investors already own technology j and are looking to add additional capacity to their power plant. If these investors are located in the left-hand tail of $f_j(C,C_j)$ they experience a levelised cost of j which is lower than the C_i and will therefore decide to invest in technology j instead of technology i – this is represented by the red shaded area. As more investors experience a higher cost for technology j – moving towards the right of the distribution curve - compared Ci investors decide to invest in technology i instead. All investors who already own technology i and enter the market to add additional capacity (or switch their current technology) experience a cost which is less than C_j, this means they purchase additional capacity of technology i (do not switch).

[6] Levelized Cost of Electricity (LCOE) is an existing framework which is used by industry to compare costs between technologies. It captures the capital cost, operating and maintenance cost, fuel cost, carbon costs associated with emissions and a discount rate.

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FTT:Power carries out this decision-making process for all available technologies to determine the

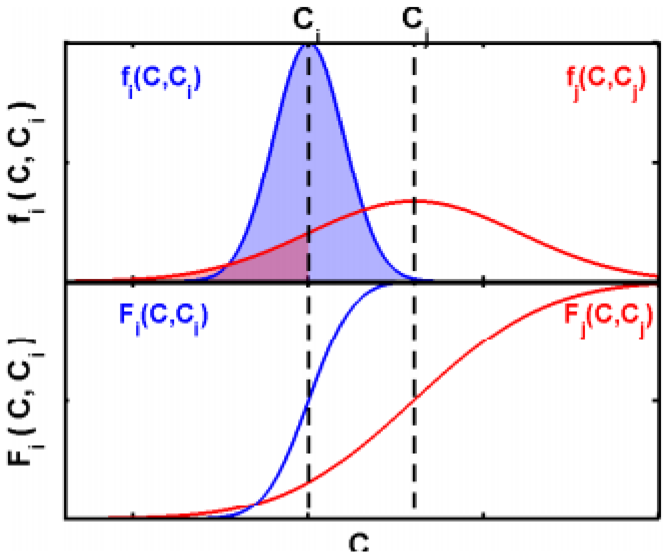

Figure 2.4: Pairwise comparison of technologies in FTT:Power

overall market share for each country in each year. There are 24 different power technologies:

Power technology		
Nuclear	Solid Biomass	Onshore
Oil	S Biomass CCS	Offshore
Coal	BIGCC	Solar PV
Coal + CCS	BIGCC + CCS	CSP
IGCC	Biogas	Geothermal
IGCC + CCS	Biogas + CCS	Wave
CCGT	Tidal	Fuel Cells
CCGT + CCS	Large Hydro	CHP

Table 2.2: FTT:Power technologies

These technologies use 13 types of natural resources:

Resource types		
Uranium	Biogas	Solar sites
Oil	Tidal	Geothermal sources
Coal	Hydro	Waves
Gas	Onshore wind sites	
Solid biofuels	Offshore wind sites	

Table 2.3 Resource types

FTT:Power determines the share of technologies in each country for a given scenario based upon detailed electricity policy: carbon prices, subsidies, feed-in tariffs and regulations by technology. Changes in the power technology mix result in changes of production costs, reflected in the price of electricity. Besides electricity prices, FTT:Power can produce aggregate outputs such as power generation investment, fiscal adjustment for subsidies, demand for other fuels and power generation CO_2 emissions.

2.1.2.2 FTT: TRANSPORT

FTT:Transport was developed by Mercure and Lam (2018) to estimate vehicle choices for passenger

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transportation. The modelling framework of FTT:Transport is similar to FTT:Power (explained in Section 2.1.2.1). It has the same decision-making core – making pairwise comparisons of different available technologies – and replicator dynamics. Although the decision making core is the same, it is “much more complex to model” vehicle choices than technologies in the power sector (Mercure and Lam, SI 2008). Unlike the power sector market, the market for private passenger Light Duty Vehicles (LDVs) contains greater product variation; the price of a vehicle can vary from €13,000 to €130,000[7] (Mercure and Lam, Supplementary Information, 2018). In addition, consumers care more about the symbolic meaning the vehicle possess (Steg, 2005) than is the case for investors in energy technologies.

This extra level of consumer heterogeneity is partly mitigated through disaggregating technologies by engine size (see Table 2.4). Recent developments of the model have also attempted to improve the representation of vehicle choices by including an income effect (Lam, 2018). Individuals with greater incomes are more likely to select vehicles with larger engine size.

Technology type	Engine size
Petrol	Econ, Mid, Lux
Advanced Petrol	Econ, Mid, Lux
Diesel	Econ, Mid, Lux
Advanced diesel	Econ, Mid, Lux
CNG	Econ, Mid, Lux
Hybrid	Econ, Mid, Lux
Electric	Econ, Mid, Lux
Bikes	Econ, Lux

Table 2.4: Vehicle fuel type and segment in FTT:Transport

It is important to note that the model does not have a mean ‘representative agent’. The distribution of vehicle prices per technology represent consumer diversity (Mecure and Lam, SI 2018). This is assumed to reflect the distribution in willingness to pay. This has to be done by assumption because we cannot explicitly observe the individual’s willingness to pay. We do not know the subjective cost that the consumer attaches to each vehicle so assume the variation in vehicle costs for different technologies and engine sizes captures this. In the model development of FTT:Transport (see Section **Errore. L'origine riferimento non è stata trovata.**) the methodology behind calculating a willingness to pay is explained.

The cost of transport technologies is represented by the Levelised Cost of Transportation (LCOT), which is an adaptation of LCOE for transport technologies. The LCOT incorporates all the components that are important to decision-making. When purchasing a vehicle, the consumer pays the investment upfront or may take out a loan. Throughout the lifetime of the vehicle, fuel and maintenance will be required. In addition, taxes and subsidies can be included, if applicable. The future costs and payments are discounted to represent the net present value.

Cost reductions are also included through a learning by doing effect. As the share of one technology increases so does the learning attached with producing the parts, which lead to cost reductions. The learning takes place at the component level meaning spillovers can occur with other technologies that are using the same components, even if the market share of that technology has not increased. The inclusion of a spillover matrix allows for this phenomenon to be captured in the modelling (Knobloch et al., 2017). This element is the same across all FTT models.

One element that differs in FTT:Transport from FTT:Power is that there are no constraints on natural resources. The supply of natural resources, such as land for wind farms, are considered in the

[7] Converted based on 2017 exchange rate from Eurostat (ert_bil_eur_a)

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FTT:Power model. But the supply of demanded natural resources for fuels and construction of passenger transportation is not constrained, except for oil and gas. There are supply constraints for oil and gas, which is a calculated in E3ME through the fossil resources depletion algorithm (Mercure and Salas, 2013).

The frequency of new vehicle additions (and therefore decisions around which type of vehicle to procure) depends on the rate at which old vehicles are retired from the stock, known as the scrappage rate. However, the two are not (necessarily) equal. At an EU level, the rate of additions to the vehicle stock is greater than the rate at which old ones are scrapped (particularly in central and Eastern Europe, where income effects continue to lead to increased vehicle take-up).

The average new vehicle is owned for between 3 and 5 years before entering the second-hand market (based upon data on the length of financing contracts). Therefore, a new purchase decision is being made every 3 to 5 years – not every 11 years as would be suggested by the survival rate (the average age of a European LDV is around 11 years). This has important implications for FTT:Transport; by incorporating shorter initial ownership periods, a more rapid diffusion of new technologies is achieved, in line with historical deployment rates.

The model solves the market share of each technology and engine size to meet a projection of private LDV passenger-km (demand for transport). It does this for 59 countries including all 28 MS and Ukraine up to 2050. Upstream emissions from fuels can also be calculated off model based on data from a report by the JRC (2014)[8]. The outputs of the model include the market share of vehicle technology type and engine size, the energy demand and the associated tailpipe CO_2 emissions.

As explained above, the model computes a market share for each technology based on the LCOT. But in reality, investors do not make decisions on costs alone (Knobloch et al., 2017). There exists a larger set of unexplained variables which can impact on the decision. Since these unexplained variables are not parameterised in the model, they cannot be included in its simulation. This means that the model results may not match the historical data. The difference between the model simulation and historic data is due to these unexplained variables, symbolised by γ. This is the calibration factor which fits the model to the historic data. For example, if the model simulates a share of electric vehicles that is lower than the historical data suggests, this could either be a function of incorrect parameter estimation, or of non-modelled factors included in the calibration factor, for example buyers placing a particular emphasis on local emissions and therefore have a higher willingness to pay for electric vehicles. The difference in shares is used to calibrate the model.

2.1.2.3 FTT: HEAT

FTT:Heat is a simulation model of technological change in the residential heating sector. It allows the simulation of likely trajectories of heating technology diffusion, based on the bottom-up representation of household decisions. Compared to FTT:Transport there is less complexity in modelling heating choices because there is less symbolic meaning and social status attached with heating technology, and therefore less heterogeneity amongst consumers. For each Member State, the starting point is an exogenous level of demand for residential space and water heating. The role of FTT:Heat is mainly to determine which heating technologies supply the given level of heat demand, and the resulting levels of fuel use, emissions and investment (by technology). Upstream emissions from fuels can also be calculated off-model based on data from a report by the JRC (2014)[9]. The model includes 13 different heating technologies (see Table 2.5) and can simulate 12 different market-based and regulatory policies, such as carbon taxes or capital subsidies (Knobloch et al., 2017).

[8] JRC (2014) Solid and gaseous bioenergy pathways: input values and GHG emissions
[9] JRC (2014) Solid and gaseous bioenergy pathways: input values and GHG emissions

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Heating technology
Oil boiler
Oil condensing boiler
Gas boiler
Gas condensing boiler
Biomass stove
Biomass boiler
Coal boiler
District heating
Electric heating
Heat pump - ground source
Heat pump - air/water
Heat pump - air/air
Solar thermal

Table 2.5: Heating technologies in FTT:Heat

The Levelised Cost of Heating (LCOH) represents the cost of technology in FTT:Heat. The LCOH incorporates all the components that are important to decision-making:

- the capital cost of the technology
- the discount rate
- the fuel cost
- maintenance cost
- additional taxes and subsidies (if applicable)

The market interest rate is used to discount the fuel and maintenance costs that a household will incur throughout the lifetime of the technology. It is also used to calculate the potential repayments if a loan was taken out to finance the purchase. For each MS and each year, a mean and a standard deviation of cost parameters that make up the LCOH are calculated to produce a distribution curve.

This distribution curve for costs reflects heterogeneous preferences of households. These

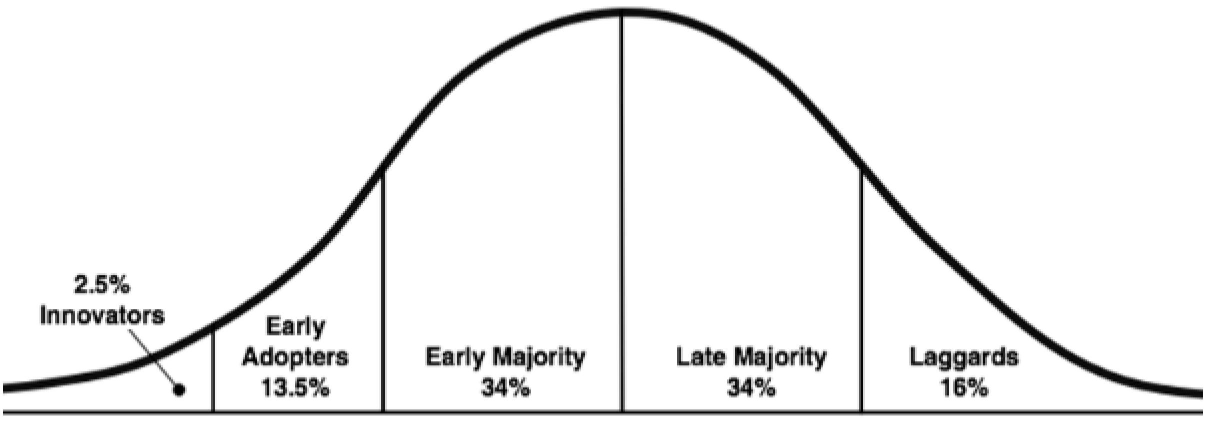

Figure 2.5: Distribution of households

preferences can arise due to living in different location, or perhaps from different types of buildings. In diffusion theory (Rogers, 2010) five different types of consumers exist: innovators, early adopters, early majority, late majority and laggards (see Figure 2.5**Errore. L'origine riferimento non è stata**

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trovata.[10]). By describing the link between diversity of households and technology diffusion theory, the importance of diversity in the model is illustrated. First, it is important to note that the variation in cost represents diversity. In this sense the model does not contain an explicit representation of households' heterogeneity, but through the variation in costs it is implied. Nor is the population explicitly broken out by these groups.

The median LCOH of technology i may be less than technology j for household A but not for household B. This implies heterogeneous preferences between the two households; technology i is more attractive for household A but not attractive for household B. In other words, household A is an early adopter and household B is part of the late majority. As costs evolve over time (explained in the earlier sections) the rate at which technology i diffuses increases. Now, household B experiences a lower cost for technology i than technology j, they find it more attractive, and hence they invest. As the cost continues to fall more and more households find that technology i is cost effective (attractive) and the rate of diffusion will increase. To highlight the importance of this design element, consider if there was no variation in cost. If diversity was not represented in the model, households would have identical preference and constraints, as soon as technology i was less expensive than technology j, every household would invest in this technology. The uptake would jump from a level of inertia to full market saturation, an unrealistic phenomenon.

Households' knowledge is assumed to be imperfect, with restricted access to information on technologies, and therefore households are less likely to choose what they do not know. Furthermore, industries are assumed to have limited production capacities, so that only a limited capacity of each technology can be produced (and set up) within each period. Including these assumptions about households and industries means the representation of technology uptake resembles the typical s-shaped diffusion curves of technology transitions. The curve is also subject to inertia: technological change does not occur instantaneously. There is a limit on the potential speed of diffusion of a technology, and this limit varies in proportion to its previous market share. For instance, a low market share of heat pumps means their diffusion will be slow, at least at the start, in the projected period. This represents the access to resources to build and sell the technology in that country. The reaction to cost changes (like new taxes) is therefore a gradual process (Knobloch et al., 2017).

One element that differs in FTT:Heat from FTT:Power is that – similar to FTT:Transport - there are no constraints on natural resources. The supply of natural resources, such as land for wind farms, are considered in the FTT:Power model. But the supply of demanded natural resources for residential heating technologies is not constrained, except for non-renewables. There are supply constraints for non-renewables, which is calculated in E3ME through the fossil resources depletion algorithm (Mercure and Salas, 2013).

The frequency of decision, i.e. the rate of diffusion of the technology, in FTT:Heat has a unique treatment that does not exist in any of the other FTT models. Instead of just purchasing a new heat technology when the old one comes to the end of its life (current treatment, summarised in the Knobloch et al., 2017 and explained in detail in Mercure, 2015) households may decide to replace the technology before this point. These premature replacements may occur when a household perceives the operations of the current system to be uneconomical (Knobloch et al., 2018). Households with perfect information and without risk-aversion would make this decision when the levelised cost of purchasing and maintaining the new technology is less than the marginal cost of running the current system. But in reality, these conditions may not exist; instead there is a lack of information and risk aversion, hence households are assumed to make this decision with stricter criteria: a subjective payback threshold (b). Premature replacements only occur when the initial investment cost (IC) spread over the subjective payback threshold, plus the marginal cost of running

[10] Source: http://blog.leanmonitor.com/early-adopters-allies-launching-product/

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and maintaining the system, is less than the marginal cost of the current system.

$$MC_i > MC_j + IC_j/b$$

The model does not extend to decisions on cooling appliances. Heating and cooling appliances are not substitutable and therefore can't be included in the same diffusion model. Furthermore, cooling devices are all fuelled by electricity, therefore there is not a need to model a shift between one electric cooling device to another, unless there are considerable efficiency gains. That being said, heat pumps can be used for both heating and cooling (Nowak, 2015). When the weather is hot, the pump can be reserved to supply the home with cooling. Which means that there is some coverage of cooling technology within the existing framework. To see more details for the treatment specific to cooling see Section 3.3.3.

FTT:Heat calculates the market share of each heating technology, the energy demand and CO_2 emissions per technology for 59 regions including all 28 MS and Ukraine up to 2050.

2.2 Macroeconomic Model E3ME

E3ME is a computer-based model of the world's economic and energy systems and the environment. It is a global dynamic simulation model that is estimated using econometric methods. E3ME was originally developed through the European Commission's research framework programmes and is now widely used in Europe and beyond for policy assessment, forecasting and research purposes. The current version of E3ME includes 59 global regions and is the most comprehensive model version of E3ME to date. This section summarises the framework and important outputs of the model. For further details, see Appendix A or the full model manual available online from www.e3me.com.

The E3ME model is based on a post-Keynesian economic framework. Agents are assumed to make decisions based on conditions of fundamental uncertainty and therefore lack the knowledge with which to optimise their behaviour. It is assumed instead that behaviour follows trends derived from the historical data (i.e. from the econometric equations). The result of this is that the level of aggregate demand in the economy determines production levels and, while the level of available resources may place an upper bound on production, there is no guarantee that all the available capacity is used.

Many of E3ME's inputs are fixed and do not vary between scenarios, including:

- the historical data
- the econometric behavioural parameters estimated from the data
- exogenous factors (e.g. population growth, non-relevant policy)
- the baseline projections

A further set of inputs, exogenous trends, are required from FTT:Heat and FTT:Transport. Note this is not usually the case as the models are fully integrated with E3ME. For more detail on the linkage between REKK's European dispatch models and E3ME please refer to Chapter 4.

E3ME can produce a broad range of economic indicators. In addition, there is a range of energy and environment indicators. The following list provides a summary of the most common model outputs:

- GDP and its aggregate components (household expenditure, investment, government expenditure and international trade)
- Sectoral output and Gross Value Added (GVA), prices, trade and competitiveness effects

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- International trade (imports and exports) by sector, origin and destination
- Consumer prices and expenditures
- Sectoral employment, unemployment, sectoral wage rates and labour supply
- Energy demand, by sector and by fuel, energy prices
- CO_2 emissions by sector and by fuel
- Other air-borne emissions
- Material demands

This list is by no means exhaustive and the delivered outputs often depend on the requirements of the specific application. In addition to the sectoral dimension mentioned in the list, all indicators are produced at the national level and annually over the period up to 2050.

2.3 Dispatch Models

2.3.1 European Electricity Market Model

The European Electricity Market Model (EEMM) simulates the operation of a European electricity wholesale market in a stylized manner.

2.3.1.1 Market participants

There are three types of market participants in the model: producers, consumers, and traders. All of them behave in a price-taking manner: they take the prevailing market price as given and assume that whatever action they decide upon has a negligible effect on this price.

Producers are the owners and operators of power plants. Each plant has a specific marginal cost of production, which is constant at the unit level. In addition, generation is capacity constrained at the level of available capacity. The model only takes into account short term variable costs with the following three main components: fuel costs, variable OPEX, and CO_2 costs (where applicable). As a result, the approach is best viewed as a simulation of short term (e.g. day-ahead) market competition.

Price-taking producer behaviour implies that whenever the market price is above the marginal generation cost of a unit, the unit is operated at full available capacity. If the price is below the marginal cost, there is no production at all, and if the marginal cost and the market price coincide, then the level of production is determined by the market clearing condition (supply must equal demand).

Consumers are represented in the model in an aggregated way by price-sensitive demand curves. In each demand period, there is an inverse relationship between the market price and the quantity consumed: the higher the price, the lower the consumption. This relationship is approximated by a downward sloping linear function.

Finally, traders connect the production and consumption sides of a market, export electricity to more expensive countries and import it from cheaper ones. Cross-border trade takes place on capacity constrained interconnectors between neighbouring countries. Electricity exchanges always occur from a less expensive country to a more expensive one, until one of two things happen: either (1) prices, net of direct transmission costs or export tariffs, equalize across the two markets, or (2) the transmission capacity of the interconnector is reached. In the second case, a considerable price difference may remain between the two markets.

2.3.1.2 Trading with countries outside the modelled region

The model only simulates the supply-demand characteristics of the European region. However, trade

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still takes place at the region's borders, e.g. with Russia or Morocco. Our assumptions regarding the cross-border trade with countries outside the modelled region is that prices in these countries are exogenously given and not influenced by the amount, or direction of the cross-border transactions.

2.3.1.3 Equilibrium

The model calculates the simultaneous equilibrium allocation in all markets with the following properties:

- Producers maximize their short-term profits given the prevailing market prices.
- Total domestic consumption is given by the aggregate electricity demand function in each country.
- Electricity transactions (export and import) occur between neighbouring countries until market prices are equalized or transmission capacity is exhausted.
- Energy produced and imported is in balance with energy consumed and exported.

Given our assumptions about demand and supply, market equilibrium always exists and is unique in the model.

2.3.1.4 Electricity product prices

The calculated market equilibrium is a static one: it only describes situations with the same demand, supply, and transmission characteristics. However, these market features are constantly in motion. As a result, short run equilibrium prices are changing as well.

To simulate the price development of more complex electricity products, such as those for base load or a peak load delivery, we perform several model runs with typical market parameters and take the weighted average of the resulting short-term prices.

2.3.2 European Gas Market Model

REKK's European Gas Market Model has been developed to simulate the operation of an international wholesale natural gas market in Europe or a broader region. The model covers the EU28, the EnC Contracting Parties, the Balkans, Turkey and Armenia. The demand and supply side of the gas market, pipeline, LNG and storage infrastructure is included on a country level. Large external markets, such as Russia, Norway, Libya, Algeria and LNG exporters are represented by exogenously assumed market prices, long-term supply contracts and physical connections to Europe.

Given the input data, the model calculates a dynamic competitive market equilibrium for 35 European countries, and returns the market clearing prices, along with the production, consumption and trading quantities, storage utilization decisions and long-term contract deliveries, as well as physical flows on the infrastructure.

Model calculations refer to 12 consecutive months. Dynamic connections between months are introduced by the operation of gas storages and TOP constraints (minimum and maximum deliveries are calculated over the entire 12-month period, enabling contractual "make-up").

The European Gas Market Model consists of the following building blocks: (1) local demand; (2) local supply; (3) gas storages; (4) external markets and supply sources; (5) cross-border pipeline connections; (6) LNG infrastructure (7) long-term take-or-pay (TOP) contracts; and (8) spot trading.

1. **Local demand** is represented by demand functions. Demand functions are downward sloping, meaning that higher prices decrease the amount of gas that consumers want to use

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in a given period. For simplicity, we use a linear functional form, the consequence of which is that every time the market price increases by 0.1 €/MWh, local monthly consumption is reduced by equal quantities (as opposed to equal percentages, for example). The linearity and price responsiveness of local demand ensures that market clearing prices will always exist in the model. Regardless of how little supply there is in a local market, there will be a high enough price so that the quantity demanded will fall back to the level of quantity supplied, achieving market equilibrium.

2. **Local supply** shows the relationship between the local market price and the amount of gas that local producers are willing to pump into the system at that price. In the model, each supply unit (company, field, or even well) has either a constant, or a linearly increasing marginal cost of production (measured in €/MWh). Supply units operate between minimum and maximum production constraints in each month, and an overall yearly maximum capacity.

3. **Gas storages** are capable of storing natural gas from one period to another, arbitraging away large market price differences across periods. Their effect on the system's supply-demand balance can be positive or negative, depending on whether gas is withdrawn from, or injected into, the storage. Each local market can contain any number of storage units (companies or fields). Storage units have a constant marginal cost of injection and (separately) of withdrawal. In each month, there are upper limits on total injections and total withdrawals. There is no specific working gas fee, but the model contains a real interest rate for discounting the periods, which automatically ensures that foregone interest costs on working gas inventories are considered. There are three additional constraints on storage operation: (1) working gas capacity; (2) starting inventory level; and (3) year-end inventory level. Injections and withdrawals must be such during the year that working gas capacity is never exceeded, intra-year inventory levels never drop below zero, and year-end inventory levels are met.

4. **External markets and supply sources** are set exogenously (i.e. as input data) for each month, and they are assumed not to be influenced by any supply-demand development in the local markets. In case of LNG the price is derived from the Japanese spot gas price, taking into account the cost of transportation to any possible LNG import terminal. As a consequence, the price levels set for outside markets are important determinants of their trading volumes with Europe.

5. **Cross-border pipelines** allow the transportation of natural gas from one market to the other. Connections between geographically non-neighbouring countries are also possible, which allows the possibility of dedicated transit. Cross-border linkages are directional, but physical reverse flow can easily be allowed for by adding a parallel connection that "points" into the other direction. Each linkage has a minimum and a maximum monthly transmission capacity, as well as a proportional transmission fee. Virtual reverse flow ("backhaul") on unidirectional pipelines or LNG routes can also be allowed, or forbidden, separately for each connection and each month. The rationale for virtual reverse flow is the possibility to trade "against" the delivery of long-term take-or-pay contracts, by exploiting the fact that reducing a pre-arranged gas flow in the physical direction is the same commercial transaction as selling gas in the reverse direction. Additional upper constraints can be placed on the sum of physical flows (or spot trading activity) of selected connections. This option is used, for example, to limit imports through LNG terminals, without specifying the source of the LNG shipment.

6. **LNG infrastructure** in the model consist of LNG liquefaction plants of exporting countries, LNG regasification plants of importing countries and the transport routes connecting them. LNG terminals capacity is aggregated for each country, which differs from the pipeline setup,

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where capacity constraints are set for all individual pipeline. LNG capacity constraints are set as a limit for the set of “virtual pipelines” pointing from all exporting countries to a given importing country, and as a limit on the set of pipelines pointing from all importing countries to a given exporting country.

7. **Long-term take-or-pay (TOP) contracts** are agreements between an outside supply source and a local market concerning the delivery of natural gas into the latter. Each contract has monthly and yearly minimum and maximum quantities, a delivery price, and a monthly proportional TOP-violation penalty. Maximum quantities (monthly or yearly) cannot be breached, and neither can the yearly minimum quantity. Deliveries can be reduced below the monthly minimum, in which case the monthly proportional TOP-violation penalty must be paid for the gas that was not delivered. Any number of TOP-contracts can be in force between any two source and destination markets. Monthly TOP-limits, prices, and penalties can be changed from one month to the next. Contract prices can be given exogenously, indexed to internal market prices, or set to a combination of the two options. The delivery routes (the set of pipelines from source to destination) must be specified as input data for each contract. It is possible to divide the delivered quantities among several parallel routes in pre-determined proportions, and routes can also be changed from one month to the next.

8. **Spot trading** serves to arbitrage price differences across markets that are connected with a pipeline or an LNG route. Typically, if the price on the source-side of the connection exceeds the price on the destination-side by more than the proportional transmission fee, then spot trading will occur towards the high-priced market. Spot trading continues until either (1) the price difference drops to the level of the transmission fee, or (2) the physical capacity of the connection is reached. Physical flows on pipelines and LNG routes equal the sum of long-term deliveries and spot trading. When virtual reverse flow is allowed, spot trading can become “negative” (backhaul), meaning that transactions go against the predominant contractual flow. Of course, backhaul can never exceed the contractual flow of the connection.

2.3.2.1 Equilibrium

The European Gas Market Model algorithm reads the input data and searches for the simultaneous supply-demand equilibrium (including storage stock changes and net imports) of all local markets in all months, respecting all the constraints detailed above.

In short, the equilibrium state (the “result”) of the model can be described by a simple no-arbitrage condition across space and time. However, it is instructive to spell out this condition in terms of the behaviour of market participants: consumers, producers and traders. Infrastructure operators (TSO, storage and LNG operator) observe gas flows and their welfare is not factored in the equilibrium.

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3 Model developments for ENABLE.EU

The development of each model is described in the sections below. The aim of the developments is primarily to improve the specifications of each model to better represent micro decision-making in line with the objectives and findings of the ENABLE.EU project.

3.1 Residential Prosumer Model

The literature as well as the initial findings from the ENABLE.EU project suggest that income and education are important factors when investing in solar PV. The results from the survey suggest that income and education together explain much of the variation in the take-up of solar PV across households. However, it is likely that these two household characteristics are highly correlated and are therefore reflecting the same behavioural trend (people with high levels of education typically also have high incomes, and vice versa).

Inclusion of behavioural characteristics related to income or education could enable us to estimate take-up among different socio-economic groups (in this case, by income group or by level of education). There are two ways in which these can be incorporated into the model.

1) Split the total population up by income band or education, to define a series of models to estimate rates of take-up among different income- (or education-) defined groups. However, there are considerable data limitations to this approach.
2) Refine the shape of the distribution of consumer preferences using data on household distributions, and to assess where on the population distribution curve different socio-economic groups are likely to sit.

3.1.1 Developing the framework

Under each methodology, take-up of solar PV among households within a specific social group will be modelled implicitly by tailoring assumptions to better reflect group-specific characteristics, with respect to the average size of homes, their location (and therefore load factor), the cost of credit and their discount rate.

The first method would involve splitting the model into three subgroups, either by income or education, for example:

- Income: Low income band - Middle income band - Upper income band
- Education: No or primary level education – Secondary and post-secondary education – Tertiary education (i.e. bachelors, masters, PhD)

Once the model is split by subgroup, the next step is to split the technical potential. The technical potential is the upper limit of solar PV investment based on assumptions about the feasible roof space. This can be done by taking a simple average, sharing the technical potential out by the number of individuals in each of the subgroups based on national statistics. However, this may be misrepresentative of the actual roof space per income group. Those in higher income groups may live in larger homes with larger roof spaces, and therefore technical potential among this group would be higher. To incorporate this element, the calculation for the technical area can be adapted to include the average size of homes in each income group. From here the discount rate (or the required rate of return) can be modified to reflect the likely discount rate these groups face and the variation in preferences of those income groups.

3.1.2 Developing the decision making rule

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Tailoring interest rates

As mentioned in the Section 2.1.1 a cost-effectiveness distribution curve is calculated to represent the net present value the household will receive from an investment into solar PV. The net present value is calculated as the difference between future benefits (e.g. from feed-in tariff schemes and future electricity bill savings) and future costs (e.g. maintenance costs). Note that the cost-effectiveness of an investment will be greater the larger the home. Individuals with larger homes will be able to install a greater capacity of solar PV, generating more electricity and therefore increasing the feed-in-tariff and electricity bill savings they receive. The mean interest rate used to calculate the net present value is the market interest rate at which households can borrow money against their mortgage (to reflect the probable decision environment of an investment by a household). It is assumed renters do not enter the market because of split incentives. However, in reality, individuals do not all face the same interest rate, as access to capital markets is not homogenous across society. Some households may be unable to get a loan with favourable conditions. When the model is re-defined for each income group, it is possible to alter the interest rate to reflect the probable restriction to finance for low income bands and better access to finance for higher income bands.

Required rate of return

Restricted access to finance is one issue low-income households may face. They may also perceive the investment as less attractive because it takes away from their purchasing power today. Although, in the long run, the household may be financially better off after investing in solar, the financial benefits are spread over time and are not available today, which can be a major issue for cash-poor households. In essence, not all households will value future payments at the same rate (Frederick et al., 2002) and this can be reflected in the model to improve the decision making module.

In the model, this element of the decision making process is captured by an assumption on the required rate of return of investment, which determines the consumer preference distribution curve. The distribution curve captures some variation in the required rate of return across households, but it will not explicitly be able to say that a proportion of the population, say, who have low incomes, will require a higher rate of return than higher-income households. Evidence from the literature suggests that the required rate of return will be higher for low-income groups of consumers. Since low-income groups place a higher value on income today than high-income groups (i.e. low-income groups have a higher discount rate), future payments will need to be larger.

The modelling assumption for the mean required rate of return on investment across the whole population is 6.2%, based on reports from Parson Brinkerhoff (2015) and NERA (2015). In a field experiment, Demark Harrison et al. (2002) found that low-income households have discount rates (partly[11] equivalent to the required rate of return) that are over 10 percentage points higher than discount rates of high-income households. This is one way in which the required rate could be altered.

The second potential model development involves adapting the consumer distribution curve to more accurately represent the distribution of preferences within a country. In previous applications, the consumer distribution curve is assumed to be normally distributed. However, in reality, the distribution of preferences among a population may be skewed. For example, if there was a large group of individuals that would not invest in solar PV (even under financially very attractive conditions) because they were not able to access funds for investment, the distribution curve would not be normal. It could instead be bi-modal or skewed.

The implication of this would be less take up of solar PV as the area under both curves would also be smaller (represented by C in Figure 3.1).

[11] Only partly equivalent because the required rate of return incorporates other factors like the administrative requirements of investment, aesthetics as well as time preference.

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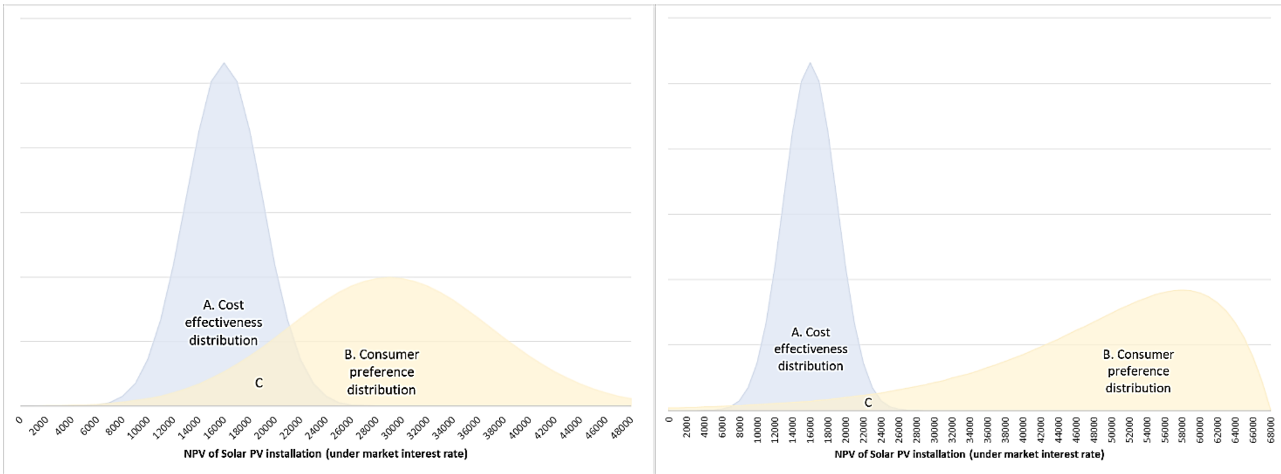

Figure 3.1: Existing treatment of consumer preferences curve (right) and new treatment of consumer preferences curve (left)

The distribution of income or other factors can be based on data from national statistical offices.

3.1.3 Limitations

The model is currently written in Microsoft Excel, and including subgroups of the population involves creating new sheets for each country. As the model includes 28 MS, Iceland and Norway, increasing this to 90 sheets will use up considerable computing power and increase the time the model takes to solve.

The technical potential calculation will be difficult to split out without the required data. An attempt has been made to split this figure across income groups but the data was inconsistent. As part of the calculation the portion of houses and flats by income group is needed and the portion of houses and flats that are rented or owned is needed. However, the data found for the proportion of houses and flat was only available for the whole population, not by income group. And the proportion of houses and flats that are rented was also only available at the whole population level. Inconsistencies like this make it difficult to split the model up.

A potential issue with determining a new consumer preference curve on income (or education) only, means we are assuming income is the main determinant of preferences. Whilst this may be true, there are other factors which are also important, such as aesthetics or administrative burden attached with solar PV, which will be excluded if the new distribution curve is solely based on income. It is therefore important to alter the calculation in such a way that this information on consumer preferences is not lost.

3.2 FTT:Transport

To incorporate additional parameters into the decision-making core, these must be converted into a cost estimate to reflect the willingness to pay. To do this, we will draw on the household survey from the mobility case study in Work Package 4[12] and additional data to perform regression analysis to

[12] ENABLE.EU conducted a nationally representative survey among the population in the 11 project's partner countries – Bulgaria, France, Germany, Hungary, Italy, Norway, Poland, Serbia, Spain, Ukraine and the United Kingdom. The survey methodology was designed to allow both in-depth analysis of country specifics and cross-country comparisons, putting a focus on three key consumption areas – heating & cooling, mobility and

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identify the significant parameters and their associated willingness to pay estimates.

The coefficients from a regression using the survey data only represent the probability of take up of different technologies. Although it may reflect a higher willingness to pay, the decision-core in the FTT:Transport model framework is based on the difference in cost between two vehicles, not the probability. In section 3.2.1 we describe our methodology to convert probability into willingness to pay.

3.2.1 Obtaining price data

As described in section 2.2.1 each vehicle technology is disaggregated by engine size. The engine size is an important component because it represents the heterogeneity of consumer choices in the transport sector. A purchase of a vehicle with a luxury engine size indicates the consumer is willing to spend more money for extra comfort or performance. If we can include the other parameters available in the survey it may improve the specification of the model thus enable a better prediction of consumer choices.

To compute the willingness to pay for these parameters for the model (disaggregated by vehicle technology type and engine size) we need data on the engine size of each vehicle the household owns and how much they purchased the vehicle for. These crucial components are not available from the survey data in Work Package 4. To address this issue we map the survey (SWP4, hereafter) to the Understanding Society Survey Wave 7 (USS, hereafter)[13], by relying on income indicators available in both surveys (Lam, 2018).

First, the income distribution from the USS will be categorised into income brackets which are consistent with the SWP4. Next, the average engine size per income bracket and technology will be derived. Each household that falls under the new categorisation will have one or several corresponding vehicle technologies and engine sizes, and an average of these will be calculated. For example, income bracket 1 may contain a petrol vehicle with an average engine size of 1000cc and a diesel with an average engine size of 2000cc. Next, SWP4 will be mapped to the USS based on the new categorised income brackets. For each respondent in SWP4 there is available information on the vehicle technology type and how many vehicles the household owns. We will assume that these vehicles will take on the corresponding average engine size calculated above. So, for example, all respondents in SWP4 in income bracket 1 with a petrol car are assumed to have an engine size of 1000cc.

The USS is only available for the UK, thus the above treatment covers obtaining data engine sizes for the UK only. To get similar information for the 10 other countries available in SWP4 we will have to make further assumptions. We assume that households in other countries, on the same income bracket to the UK are likely to purchase the same engine size, therefore take on the average engine size of the vehicle. The precise level of income associated with each bracket will vary by Member State, but in purchasing power terms we expect the difference to be negligible as the cost of vehicles should also be less.

The next assumption made is the inclusion of vehicle prices for each vehicle technology and engine

use of electricity, as well as governance and prosumers' issues related to the energy transition. The survey methodology includes specific blocks of questions covering each of the case studies' topics to improve our understanding of the drivers and barriers, affecting the individual and collective energy choices across the countries.

[13] Understanding Society is the largest longitudinal study in the UK carried out by the Institute for Social and Economic Research (ISER) at the University of Essex. The survey collects data from around 40,000 households on a wide range of topics.

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size. In FTT:Transport we have the price for different technologies and engine sizes in each country, this will be used as a proxy. After this exercise is complete we will know, for each country included in SWP4[14] and each household, the number of vehicles they own, the type of technology these vehicles embody, the average engine size and the willingness to pay. The average vehicle price in the UK will be adjusted based on the Power Purchase Parity (PPP) between the UK and the respective country.

3.2.2 Developing the decision making core

Once we have all the price data we can run regressions to derive the willingness to pay related to socioeconomic, demographic and environmental variables. The dependent variable will be car price per capita: the total price of each vehicle the household owns divided by the number adults (over 18) in the house (available from SWP4). The independent variables to populate the model will be chosen based on the most important factors of take up based earlier work packages. The following equation is an example of the final equation after the regression, with one per country:

$$\hat{Y} = \propto + \hat{\beta}_1 D_{electric} + \cdots + \hat{\beta}_2 education + \hat{\beta}_3 age + \hat{\beta}_4 prosumer + \cdots + \hat{\beta}_n X$$

The alpha term, or intercept, represents the minimum price individuals in a country are willing to pay for transportation. The beta coefficients for each variable will represent the change in the willingness to pay arising from that variable, for example $\hat{\beta}_2$ represents the extra willingness to pay for a vehicle given an increase in the level of education. $\hat{\beta}_1$ is a vehicle technology dummy, representing the additional amount individuals in a country are willing to pay for an electric vehicle. There will be one dummy variable for each vehicle technology.

These coefficients, which represent the willingness to pay of a particular parameter, will then be grouped together to form an index giving the overall willingness to pay of each parameter. This will then be incorporated into the LCOT:

$$LCOT\ withWTP_{i,k} = LCOT\ noWTP_{i,k} + WTP_{i,k}$$

LCOT with WTP is the new LCOT after adding WTP, whereas LCOT_noWTP (i,k) is the old LCOT with addition WTP. `i' is the vehicle technology (by engine size category) and k indicates the country.

After this we will have the willingness to pay across 11 EU Member States. To estimate willingness to pay estimates for the rest of the Energy Union we will use an extrapolation technique similar to the one used by Lam (2018). In Lam's (2018) thesis the willingness to pay arising from income, called the income effect, was calculated for six regions. This was extrapolated to the rest of the 59 regions in E3ME based on the power distance index developed by Hofstede's dimension of national culture (Hofstede, 2010). The power distance index represents the "extent to which less powerful members of organisations and institutions accept and expected that power is distributed unequally" (Lam, 2018). By running regressions with demographic and economic data as well as the power distance index Lam was able to derive estimates for the other regions. For example, if the country scored highly in the power distance index, i.e. the country has greater acceptance of inequality, it is more likely that social status would be visible (e.g. through the vehicles they buy). The regression would then estimate a greater income effect for those countries. We will apply this framework, but the cultural index (i.e. the power distance in the case of income) is yet to be defined since first it is necessary to identify which variables will be used to define the willingness to pay.

3.2.3 Limitations

[14] Bulgaria, France, Germany, Hungary, Italy, Norway, Poland, Spain, Ukraine and the United Kingdom

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There are a few limitations to the proposed methodology. It might be the case that the average price of the engine size of a certain vehicle is missing from the USS. If someone from the SWP4 owns a vehicle that was not in the USS there will be no average price for that vehicle. In this case additional data sources will need to be used in order to make an assumption for the size of the engine and its average price. If supplementary sources are inadequate, one way in which we might resolve this issue is to interpolate between the different income groups. This will require having the adequate data in the income group above and below the one with the missing data.

Another limitation is the lack of data for other countries and therefore the assumption that the average price of vehicles in the UK are the same as the average price of vehicles in the other countries. Whilst we take steps to account for the potential difference (i.e. using PPP) it would be more satisfactory if similar datasets where used for the other countries.

The main challenge with the regression is determining the average car price in the future as the socioeconomic factors etc. change over time. As these factors change so will the willingness to pay. The data we have is cross-sectional; because we lack a time series, we cannot extrapolate into the future. To solve this issue, we will attempt to carry out sensitivity analysis by changing the parameters to see how the variation in the willingness to pay will change. For example, one sensitivity could be to increase the level of education and see if this increases the willingness to pay for low-carbon vehicles.

This involves ambitious extensions to the model, and requires a number of assumptions to be made. These assumptions have been justified above; it is our belief that the approaches and assumptions identified above are the best approach available to adapt the model to better meet the needs of the ENABLE.EU project.

3.3 FTT:Heat

Compared to the mobility case study (FTT:Transport) a different approach will be explored in the heating & cooling case study. Here we will attempt to incorporate different subgroups into the model by splitting the population up. This will involve running the decision making core for each subgroup with possible alterations to the calculation. The methodology outlined here is similar to the one used for defining representative agents in the MESSAGE-Transport model (an integrated assessment framework) by McCollum et al. (2017).

Research conducted in other work packages of ENABLE.EU provides us with new information about which factors in the decision making process for heating technology are important. This knowledge will inform how we decide to split the population into subgroups. For example, the survey results show that characteristics of the house such as the type of home was an important factor because it restricts or enables the household to make a certain decision. A detached house with a garden will have adequate space for heat pumps, but apartment living is space-constrained and therefore is less likely to invest. The model can then be split into different types of homes to determine if the take up of heating technologies varies across these subgroups. Note that this is just one example of how the model can be split, further examples are set out below. Until the groups are tested in the model it is not possible to know which is the best approach – so we will iterate the different identified subgroups to identify a suitable set.

3.3.1 Developing the framework

As well as rewriting the code for FTT:Heat in Python, the model will be adjusted to accommodate the proposed changes. Currently, for a given year the model will loop through each country and execute the decision making core, of the whole population, to determine the share of technology. Once it has done this for each country it moves onto the next year and repeats the process. Splitting

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the population will mean including an additional dimension. So instead of running the decision-making core once for the whole population it is run for each subgroup, the take up for each subgroup will then be stored before it is summed to be used in the next iteration.

Once this modelling framework is set up it is possible to change the split of the population and test the results. From the initial analysis and literature, these are some possible ways in which the population can be divided:

- Location: Urban - Rural
- Home type: Apartment - Semi-detached – Detached
- Dwelling age: pre 1959 – 1960 to 1989 – 1990 to 2017
- Income: Low – Middle - Upper
- Tenure: Renter - Owner

It is possible to include more than one split, perhaps tenure and home type, however with each additional grouping the number of possible combinations increases, not just by the sum of the additional subgroups but by multiplication. With this split the model decision core will need to be run six times, one for every possible combination: renter in an apartment, renter in semi-detached etc. Whilst this is possible, it is more prudent to start with one group and test the model and include additional groups, if necessary.

The population will be split based on the shares available in the SWP4, and other data sources if necessary (i.e. tenure). The way the model solves the share of technology is based on the useful demand for heating energy, which currently represents the useful demand for the whole population. Splitting the population in the model means splitting up this useful energy demand. A simple treatment would be to multiply the share of households in SWP4 by this useful energy demand. However, this might not be representative of the actual useful energy demand of each subgroup. Detached houses may use more energy than apartments even though they represent a smaller share of the market. To account for this discrepancy a better treatment would to be use a weighted average. For home type, the size of home or the spending on heating can be used to weight the shares.

A further consideration is how the shares of the subgroup will develop over time. This is more complicated because there is insufficient data on the turnover of the housing stock and projections of future developments. Will more semi-detached houses be built in the future or more detached houses? To resolve this issue, we will turn to external sources to project shares forward. For location by using the UN World Urbanization Prospects (2018). The split of the location, based on the data from SWP4 was city, suburb and countryside but only for 2017. The projections from the UN cover urban and rural areas only but project out to 2050 for all countries.

For countries that are not included in the SWP4 we will not have the relevant shares to split the population. For location this is not a problem; as mentioned above the UN covers each country. But if shares are to be split based on the other groups further data needs to be collected on the historic share as well as the potential future share. The historic distribution of population by dwelling type can be collected from Eurostat[15].

3.3.2 Developing the decision-making core

We plan on adapting the decision-making core to be more representative of the decision that a particular subgroup would make. That also means this process is entirely dependent on how the subgroups (split of the population) are defined. If the split is based on the housing characteristics it

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will be necessary to either adjust the restriction matrix to reflect the constraints that subgroup face or to adjust the decision-making algorithm.

The restriction matrix in the model determines whether switching between one technology to another technology is possible. It reflects the comfort level associated with the current heating system. "This means that we do not allow a change to a heating system with a significant lower comfort and degree of automation: Coal and wood log boilers are only options in case that either coal or wood log is the existing main energy carrier. If natural gas or electricity are the main energy carriers, oil based heating systems are excluded." (Knobloch et al., 2017). We can use this existing framework to reflect the likelihood of investment between different subgroups. An apartment-owner may be less likely to invest in a renewable heating solution than the owner of a detached house (e.g. because of space). We can reflect this in the restriction matrix by populating the switching from the status quo to renewable heating solutions with the coefficients from the regression analysis. The coefficient from the regression analysis represents the likelihood of investment in renewable energy sources based on living in one type of home to another.

If the subgroup is based on tenure we could either turn off premature investments in new heating technologies altogether for renters or adjust the decision-making algorithm to reflect the probable criteria of investment of each group: assume owners consider investment costs only and not the fuel cost, and renters only consider the fuel cost and not the investment cost. A common issue is that known as split incentives, whereby the renter feels the burden of replacement is with the owner. And the owner is unwilling to invest in better technology as the rewards would not be reaped by him/herself, as the renter pays the bill. Melvin (2018) reports underinvestment occurs in heating technologies and residential energy efficiency measures due to split incentives and asymmetric information.

Another method to split the population is income. Households in the lower income bound will have less disposable income to purchase heating technology which will have adverse effects on take up of renewable heating solutions. Around 50% of the respondents (from France, Germany, Hungary, Spain and Ukraine excluding those households who answered ‘do not know’) said they do not have enough money to invest in refurbishment or supplementary insulation. The decision-making core can be altered in similar ways as developments to the prosumer model (see Section 3.1).

3.3.3 Limitations

Due to data limitations the shares of subgroups are likely to be held constant in the projected period. To our knowledge there is no source which projects, for example, the share of renters into the future. Moreover, it is quite speculative to make this assumption as in 2050 the preferences, of tenure or location, may change. Therefore, in the absence of other data, it is likely that these will be held constant.

There will be no modelling of micro decisions for cooling. Instead cooling with be modelled through assumptions of the deployment rate and trend of cooling appliance efficiency.

The modelling of the deployment of household cooling technologies will adopt a substantially different methodology to those outlined above. The range of active cooling technologies is much more limited in Europe (dominated by air conditioning units), and the project team does not have access to an existing micro model which can be expanded in the same way as the other micro models. Given that detailed data on cooling technologies has not been collected during the earlier parts of this project, a more limited modelling approach has been developed to estimate the impact of future deployments of such technologies. This will capture the impact of exogenous deployments of electrical cooling technologies (i.e. air conditioning units), taking into account continued evolution of the characteristics of such units (in terms of energy efficiency).

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In 2014 the demand for space cooling made up 1% of the total final electricity consumption of households[16]. This reflects the fact that active cooling is currently relatively limited in terms of deployment – more common in southern and western EU Member States, reflecting greater need for cooling technologies in MS where the average temperature is higher, and that ability to pay is greater in Western Europe. However, in the future both of these trends are expected to change, as climate change leads to increases in average temperatures and, more significantly, to an increase in the number of cooling degree days (CDD) during summer, defined as those days where the average temperature is above 65° Fahrenheit (18° Celsius), the level above which buildings are estimated to need cooling. The deployment of cooling technologies is therefore expected to expand at a rapid rate compared to historical deployments. As such, while the deployment of such units in the scenarios will be provided as an input to the modelling, this would be expected to follow the s-shaped diffusion curves seen in other emerging technologies – although the technology is more established, it is reasonable to assume that take-up will ramp up in a non-linear fashion as costs fall and (potentially) need increases.

In addition, the characteristics of the units deployed will also change. Air conditioning units have become substantially more energy efficient in recent years, partly in response to the "Eco Design" Directive. We will estimate future changes in energy efficiency based upon an econometric estimation of the average rate of change over the past 20 years, and apply this going forwards as a proxy for technology-specific efficiency improvements.

As such, the modelling of the impact of deployment of cooling technologies will be modelled as a function of three distinct variables;

- An exogenous deployment of electric cooling technologies across Europe (split into at least two groups of Member States, reflecting anticipated different deployment rates in these geographies), which varies by scenario.
- Changes in energy efficiency, estimated based on historical data (and not anticipated to vary with deployment, i.e. it will be constant across scenarios).
- Usage of installed cooling technologies; the energy consumption associated with the deployed cooling technologies will also depend upon the number of CDDs. We will take external projections of the number of CDDs in the different Member States to provide projections of the usage (and therefore total electricity consumption) of an individual unit in the Member State groupings used.

The exogenous deployments will be elucidated during the agreement of the scenarios, which will involve taking on views from all consortium partners based upon the evidence gathered across the other work in ENABLE.EU, as well as previous modelling exercises undertaken both by project partners and other organisations, including modelling exercises carried out for/by the European Commission.

3.4 Dispatch Models

3.4.1 European Electricity Market Model

Several model development activities were carried out in the electricity and gas market models of

[16] EU Heating and Cooling Consultation Forum (2015). *Decarbonisation of heating and cooling use in buildings.* Accessed on 12/10/2018 here: https://circabc.europa.eu/webdav/CircaBC/Energy/Energy%20Efficiency/Library/Heating%20and%20Cooling%20Consultation%20Forum%20-9%20September%202015/Issue%20Papers/Consultation%20Forum%2009092015%20-%20Issue%20Paper%20I%20-%20Decarbonisation%20of%20heating%20and%20cooling%20use%20in%20buildings.pdf

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REKK during the last 6 months. The electricity model (European Electricity Market Model, EEMM) was updated with the most recent information on the covered countries (EU 28 plus the rest of ENTSO-E countries (e.g. West Balkan countries: Bosnia and Herzegovina, Serbia, FYR of Macedonia, Kosovo, Montenegro and Albania; Turkey). This included updating the demand forecast based on latest ENTSO-E data, the power capacities pool, covering the retiring and newly built units, where the main source of information are the websites of the national system operators and utilities and the Platts database (Platts, 2018). The interconnection capacity data (Net Transfer Capacities, NTC) were also revised according to the latest ENTSO-E Ten Year Network Development Plans (ENTSO-E TYNDP 2016 and 2018). This means that the EEMM model represents the most updated set of data covering the European electricity sector.

A second development in the EEMM was building in the option of Demand Side Management (DSM) measures. DSM measures can have significant impact on the operation of the electricity system through peak savings, which helps to satisfy given demand at lower costs due to savings in peak capacities. By introducing this new option in the model, these savings could be calculated if the other WPs of the projects could provide information on the future DSM activities of consumers or on their willingness to participate in such activities.

3.4.2 European Gas Market Model

Concerning the European Gas Market Model (EGMM) development, the model went through an update of the main infrastructure developments planned in the coming 10 years, by considering projects in a FID status included in the Ten-Year Network Development Plan (TYNDP) of ENTSOG. Moreover, major pipeline projects such as Nord Stream 2 and TurkStream strings were also included. These infrastructure developments determine the market outcomes in Europe and heavily affect the transit role of Ukraine. Tariffs were updated with the latest available TSO data publication. LNG and storage infrastructure developments were also part of the data update.

Moreover, entry tariffs from domestic producers and exit tariffs for domestic consumers were incorporated. This allows for the better representation of the internal market and the modelling of retail markets.

3.4.3 Build up the iteration protocol of EEMM and EGMM

A third main development was to elaborate the protocol for harmonising and iterating the electricity market model and the gas market models (EEMM and EGMM). This means, that EEMM electricity volume outputs are fed into EGMM as gas demand outputs, then EGMM price inputs are fed into EEMM as fuel price inputs. The demand and price data are exchanged between the two models until convergence in the results is reached. This enables us to have more reliable and integrated results of various electricity and gas market related policies. This is an important development in the Enable project, as the interrelation between the electricity and gas sectors through the gas-based power production is well known but with sectoral models very difficult to capture. E.g. if in the gas markets the assumed energy savings in the heating & cooling sector (based on the respective WPs results of the Enable project) are accounted for, then this gas saving will have an influence on the other sectors (e.g. in the power sector). This impact can be highlighted with the iteration of the two models. With this process the synergy and rebound effects between the sectors could be quantified.

3.4.3.1 Detailed description of the tested iteration mode

In this section the main steps of the tested iteration mode are described. Basic input data sources (on oil price developments) were harmonised between the two models (EEMM and EGMM) and for the main scenario assumptions. Then a joint reference scenario building for the electricity and the gas infrastructure modelling was carried out.

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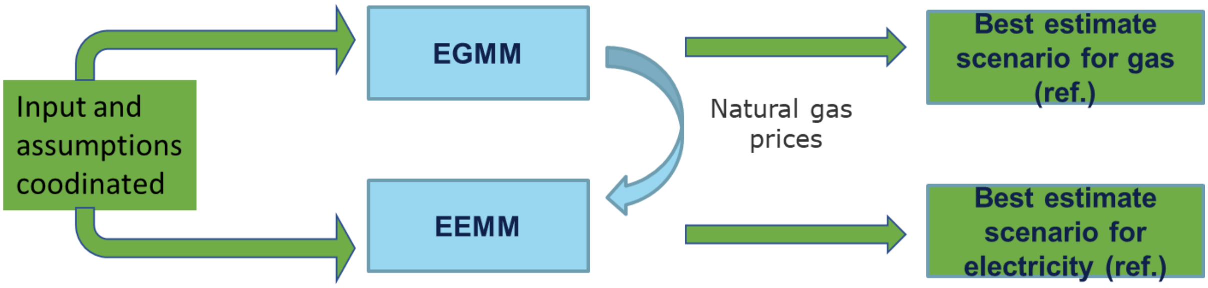
Figure 3.2: Illustration of the reference scenario building



We have iterated the models to ensure that the assumed gas price and the corresponding gas consumption levels are coherent within the two models. We first ran the gas model (EGMM) and fed the modelled gas prices into the electricity model (EEMM). In Step two the electricity model defined the gas usage in the power sector for each country, and this information was fed back to the gas model. Then in the next step the gas model was run again, and the new gas prices were again fed into the electricity model. We iterated the models as long as the results converged. We found that after 6- 8 iteration rounds the change in demand/price was on average below 1%, and at this point we stopped the iteration. This way the reference scenario for the electricity and the gas models was defined in a coordinated manner.

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4 Model integration

Figure 4.1 provides an overview of how the different models will be linked together to allow the consistent modelling of the macro modelling of the impacts of policies which impact upon individual household behaviours with respect to energy consumption.

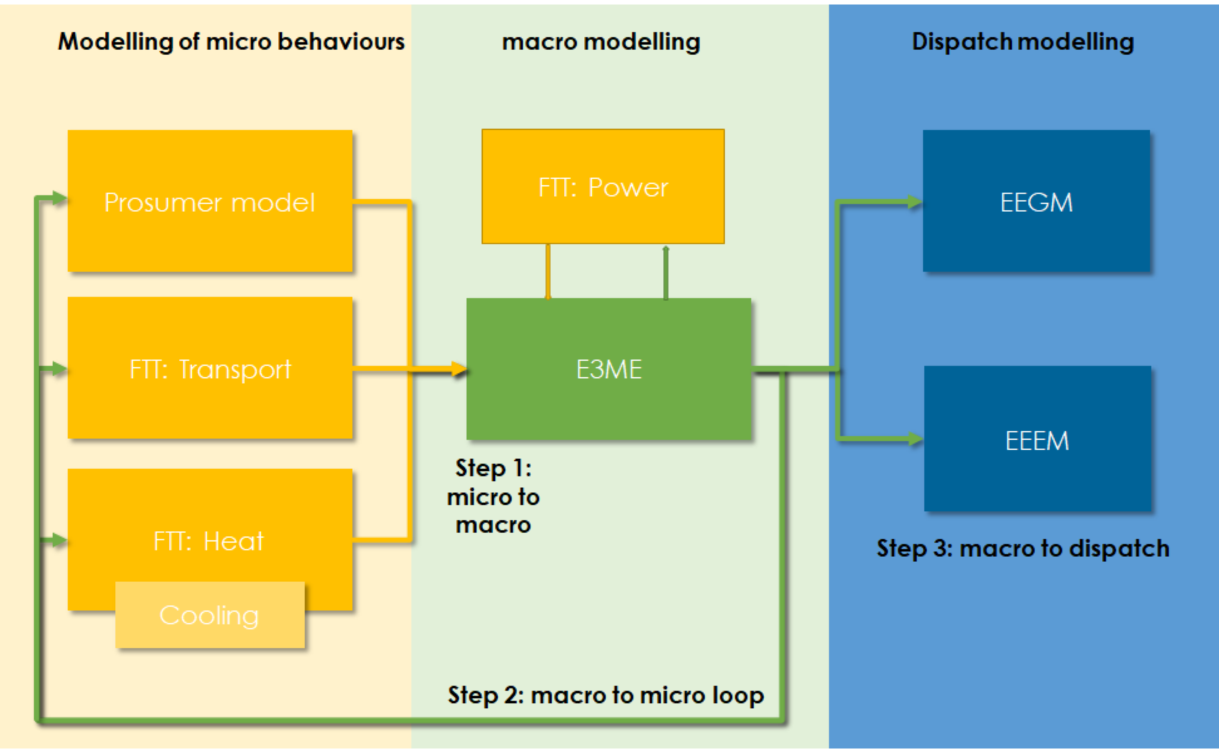

Figure 4.1: Model Integration

Through the technology diffusion models and E3ME, the impact of decisions by households at the micro-level are linked to economic and environmental macro-level outcomes. However, to reflect the changes in the European gas and electricity markets as a result of the transition to alternative technologies, a link is introduced between EEGM/EEMM and E3ME.

In the rest of this chapter, we discuss the links between the different models in more detail.

4.1 Step 1: Micro to macro modelling

The three different approaches being used during WP7 have different strengths & weaknesses, as well as different coverage of indicators and impacts. As such, it is necessary to link them in order to fully understand the implications of the policy scenarios to be modelled (which are discussed in more detail in Section 5). The first stage in this linkage is using outputs from the micro models (the prosumer, cooling, FTT:Transport and FTT:Heat models) as inputs to the macro model (E3ME).

The micro-level models will provide data on energy consumption by fuel, and changes in expenditure on specific consumer expenditure categories (for example, an increase in expenditure on motor vehicles which would accompany a shift from internal combustion engines to electric vehicles due to the latter's higher purchase price). These indicators will then be used as inputs into the macro model, in order to, in the first instance, determine selected fuel prices (more details on this are provided in the following section).

Each micro model is considered separately below.

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4.1.1 FTT:Transport

FTT:Transport will output the market shares of vehicles and the associated energy demand for each of these vehicles. There are four different fuels types which map straight to the fuel types available in E3ME: Middle distillates, electricity, natural gas and hydrogen. These fuels map to the classifications in E3ME (see Table 4.1).

FTT:Transport	E3ME
Petrol and diesel	Middle distillates/biofuels
Electricity	Electricity
Gas	Natural Gas
Hydrogen	Hydrogen

Table 4.1: Mapping fuel types from FTT:Transport to E3ME

These adjustments will then be fed into the demand for fuel from the road transport sector in E3ME, and replace the current econometric estimation. For example, if there is an increase in the number of electric vehicles and a fall in the number of petrol and diesel cars, there will be an increase in electricity fuel use and a decrease in middle distillates. We will then adjust the demand for electricity and middle distillates accordingly.

In addition, changes in consumer expenditure will also be incorporated. FTT:Transport does not explicitly calculate the change in expenditure on motor vehicles, but this will be done off-model, reflecting evolutions in average vehicle costs as a result of the greater share of advanced (non-ICE) powertrain vehicles.

Tailpipe emissions can be calculated by applying emission factors to the demand for different fuels which is output from FTT:Transport. This is a standalone result and does not need to be fed into the E3ME model.

4.1.2 FTT:Heat

FTT:Heat will produce a time series for each EU MS of the fuel use of residential heating technology for six different fuels: coal, oil, gas, electricity, district heat and biomass/wood. These fuels map to the classifications in E3ME (see Table 4.2).

FTT:Heat	E3ME
Coal	Hard coal
Oil	Middle distillates
Gas	Natural Gas
Electricity	Electricity
District heat	Heat
Biomass/wood	Biofuels

Table 4.2: Mapping of fuels types from FTT:Heat to E3ME

Each time series will be converted from GWh to tonnes of oil equivalent (toe) to be consistent with the units in E3ME. The times series will also be scaled, based on the respective ratio of FTT:Heat fuel use relative to E3ME fuel use in 2014, for each fuel type (Knobloch et al., 2017). Then the fuel use will be inputted into E3ME where it replaces heating component of residential fuel use (assumed to be 100% of residential fuel demand), i.e. the econometric estimation of this component is

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completely replaced by the output from FTT:Heat. This process will be done for all fuels – although it represents only one part of total household electricity consumption. In order to calculate the overall impact of the scenarios on household electricity consumption, the outputs of all micro models will be summed.

For all of the different components of household electricity consumption, a similar methodology will be adopted;

1) Calculate the historical share of household electricity consumption devoted on heating
2) Assume that, in the reference case, the proportion of consumption allocated to this purpose will follow historical trends
3) Remove this 'baseline' estimate from total household electricity consumption
4) Add in the explicitly-modelled consumption from the micro model (in this case, FTT:Heat)

In following these steps, we are ensuring that there is no double-counting of electricity consumption. This replicates the treatment that is currently carried out in E3ME, where versions of the FTT models are already implemented.

4.1.3 Cooling model

The cooling model will estimate the household consumption of electricity, based upon trends in deployment and energy efficiency. The key output from this work, which feeds in to E3ME, is the extent of household electricity consumption that is required for cooling. This will be calculated within the model, and the displaced volume of consumption in the baseline estimated using the method outlined in section 4.1.2.

In addition, based upon trends in the costs of the technology, we will estimate the total value of consumer expenditure required over time to purchase the cooling units that are deployed in the scenario - this will displace consumer expenditure in other categories in E3ME (i.e. additional spending on the technology will reduce expenditure by consumers on other goods and services, before considering the impact of changes in the wider economy on overall levels of consumer spending).

4.1.4 Prosumer model

The output of the prosumer model is the number of households with solar PV installations. Through assumptions regarding the level of solar insolation in each country and the efficiency of the panels this can then be converted into prosumer electricity generation.

We will then remove this from the electricity generation demand by households calculated using data from E3ME and the other micro models. There is no explicit treatment of reduced individual consumption versus feeding electricity back into the grid – i.e. we treat the two the same, as net reductions in electricity demanded from the grid.

4.2 Step 2: Macro to micro modelling

FTT:Energy, operating within E3ME, determines fuel and electricity prices based upon the cost-supply curves built within the modelling framework. Since these prices play a key role in determining the costs, and therefore takeup, of the different technology options, it is necessary to ensure that these are reflected in the micro modelling. Therefore, an iterative link between the macro and micro modelling is required. This mimics the existing treatment within the fully-integrated version of E3ME (where FTT:Transport and FTT:Heat sit within the macroeconomic model). E3ME determines fuel prices for a given deployment of technologies, which are then fed back into the micro models to determine micro-level responses to these prices, altering take-up and therefore demand. Based

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upon the cost-supply curves within FTT:Energy, new wholesale prices are calculated, and linked back to the micro model, etc. This loop is repeated until supply and demand between the two sets of models converge.

In cases where the models fail to converge, we will seek to understand what is leading to a lack of convergence and address the root cause; however, should it prove impossible to reach convergence, a maximum limit will be put upon the iterations between the two frameworks, and the loop broken at that point.

4.3 Step 3: Macro to dispatch

In the final link between models, we take selected output from the second run of the macroeconomic model, E3ME, and use these as inputs to the two dispatch models, EEMM and EGMM. The aim of this linkage (and link 3 outlined below) is to ensure that consistent energy and fuel prices are being used in all models.
Some assumptions are introduced exogenously into both models; the oil price will be taken from the IEA World Energy Outlook 2018 (the precise WEO scenario from which the assumption will be taken for each of the scenarios modelled will be discussed during the formulation of the baseline and the scenarios, discussed in more detail in Chapter 5). Gross (non-household) energy consumption in the reference case will be drawn from the PRIMES Reference Scenario 2016.

The two dispatch models will take other inputs from E3ME and FTT:Power[17]. For example, national coal prices are calculated endogenously within FTT:Power (based upon country-specific cost supply curves). However, natural gas prices will be calculated within EGMM, based upon the aggregate demand for household and industry gas drawn from E3ME. Demand for other fuels will also be drawn from E3ME, alongside the associated prices.

The dispatch models then calculate short-term wholesale prices based upon the specific manner in which electricity markets operate in the EU Member States (and reflect merit order effects as relevant) to provide additional insight into the impact of the scenarios of each scenario.

[17] FTT:Power is integrated into E3ME to calculate the share of electricity generation by technology.

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5 Scenario modelling

The ENABLE.EU foresight process as part of WP6 focusses on the identification of possible transition pathways and policy measures with the engagement of stakeholders, experts and households. By quantifying the scenarios to the extent possible using the above outlined modelling framework, ENABLE.EU aims at offering further insights into the potential costs and benefits of the transition pathways and a range of policy measures.

At the first workshop with stakeholders (i.e. the Transition Visioning Workshop), seven priority areas were identified, along with measures that could be promoted today to move from the current energy system toward a more sustainable one. The second workshop will aim to validate these areas and investigate what citizens perceive as the most important obstacles and opportunities in order to adopt and realize the measures proposed.

The more research findings emerge from the case studies and the further the discussion on scenarios takes shape, the easier it becomes for us to translate the most relevant policies and desired shifts into the modelling framework. However, while there will be overlaps with the qualitative visioning scenarios, it should be clear that there are methodological restrictions to the quantitative modelling (i.e. data and resource availability).

5.1 Reference scenario

Analysis of the impacts in the scenarios requires a comparison against what the outcomes would have been in the absence of intervention. This information is found in the reference scenario, and the differences in outcomes between the results in the reference scenario and the results in the policy scenarios are attributed to the policies that are assessed. The reference scenario will broadly reflect a 'business as usual' situation and reflects measurements of key conditions, or indicators, from which change and impacts can be assessed.

Baseline data contained in the reference scenario vary depending on the type of analysis that is performed and the model that is being used. It can include data for demographic indicators, labour productivity and GDP growth, energy consumption and emissions, education, public spending, trade, etc. Baseline data for a number of these indicators are commonly calibrated to published projections (e.g. EU Reference Scenario 2016).

The baseline of the E3ME model to model future impacts can be viewed as an 'uncontroversial yet timely projection' of the future path of the EU-28 that embodies accepted trends. In similar policy impact work for the EC this is taken to be based on the long-term trends and assumptions published in DG Energy publication EU Reference Scenario 2016, Energy, transport and GHG emissions: Trends to 2050 (published in 2016), with more current assumptions for particular variables where available.

It is yet to be discussed with the partners which published projections and indicators are to be included in the reference scenario. A key issue to be discussed is the extent to which the reference case should include only 'current policy', i.e. that which has formally been agreed and entered onto the statute books (and as of what point in time), or whether it should include, to some extent, existing commitments (e.g. stated EU energy efficiency goals), even though specific policies may not have been introduced to meet these.

5.2 Policy scenarios

The scenarios will reflect possible futures rather than a detailed forecast of the future. These

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‘possible futures’ reflect potential changes in the EU economy towards 2050 and should be seen as ‘what if’ scenarios rather than forecasts of the most likely future. They provide a narrative on possible futures as well as assess the economic, environmental and social impacts of these.

In the FTT:Heat, FTT:Transport and the Residential Prosumer models, we can design and implement policies to influence household decisions and assess the impact on the take-up of technologies. In other words, ‘micro-scenarios’ can be developed to influence some of the behavioural characteristics (or other important factors) of individuals which have a strong positive effect on energy technology take up in the case study areas (transport, heating & cooling, solar PV). The impact of these ‘micro-scenarios’ on the wider economy can be assessed though the link with the FTT:Power model and E3ME.

In FTT:Power and E3ME we can also look at the bigger whole-economy shifts, and the interconnection between the power sector and other sectors. Policies designed to speed decarbonisation in the power sector can have significant impacts on, for example, overall levels of investment in the economy and vice-versa; changes in economic policy can bring about changes in investment costs or the total energy demand from the economy. E3ME further allows an assessment of the impact of broader economic policies, such as the impact of increased spending on innovation, a shift towards a circular economy, or spending on education and human capital formation.

With EEMM and EEGM we can assess the impacts of changes in the energy system in more detail on the electricity and gas system: on prices, quantities, emissions - not only the change in the quantity of consumption but its pattern (e.g. DSM measures) will have significant impacts on system operation and performance. Changes can take place in many directions: while energy savings would reduce the overall energy consumption, electric mobility on the other hand would increase electricity consumption, with a possibility of even higher volatility in hourly consumption patterns.

In the modelling scenarios for ENABLE.EU, different combinations of policies, or higher levels of the same policy, can be constructed to gain a comprehensive set of results which we can then compare in the final stages of the project to enable critical analysis and policy recommendations to be developed. This is to be discussed at the next coordination meeting in November 2018 in order to ensure consistency with the project’s objectives and interests of the consortium partners.

At that meeting, we will present a comprehensive overview of the transitions and policies we can assess with the integrated modelling framework presented in the previous section of this working paper. This should set the scene for further discussions on which transitions and policies to include in the ENABLE.EU modelling scenarios.

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Appendix A E3ME model description

Introduction

E3ME is a computer-based model of the world's economic and energy systems and the environment. It was originally developed through the European Commission's research framework programmes and is now widely used in Europe and beyond for policy assessment, for forecasting and for research purposes.

Recent applications of E3ME include:

- a global assessment of the economic impact of renewables for IRENA
- contribution to the EU's Impact Assessment of its 2030 climate and energy package
- evaluations of the economic impact of removing fossil fuel subsidies in India and Indonesia
- analysis of future energy systems, environmental tax reform and trade deals in East Asia
- an assessment of the potential for green jobs in Europe
- an economic evaluation for the EU Impact Assessment of the Energy Efficiency Directive

This model description provides a short summary of the E3ME model. For further details, the reader is referred to the full model manual available online from www.e3me.com.

E3ME's basic structure and data

The structure of E3ME is based on the system of national accounts, with further linkages to energy demand and environmental emissions. The labour market is also covered in detail, including both voluntary and involuntary unemployment. In total there are 33 sets of econometrically estimated equations, also including the components of GDP (consumption, investment, international trade), prices, energy demand and materials demand. Each equation set is disaggregated by country and by sector.

E3ME's historical database covers the period 1970-2014 and the model projects forward annually to 2050. The main data sources for European countries are Eurostat and the IEA, supplemented by the OECD's STAN database and other sources where appropriate. For regions outside Europe, additional sources for data include the UN, OECD, World Bank, IMF, ILO and national statistics. Gaps in the data are estimated using customised software algorithms.

The main dimensions of the model

The main dimensions of E3ME are:

- 59 countries – all major world economies, the EU28 and candidate countries plus other countries' economies grouped
- 43 or 69 (Europe) industry sectors, based on standard international classifications
- 28 or 43 (Europe) categories of household expenditure
- 22 different users of 12 different fuel types
- 14 types of air-borne emission (where data are available) including the six greenhouse gases monitored under the Kyoto protocol

The countries and sectors covered by the model are listed at the end of this document.

Standard outputs from the model

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As a general model of the economy, based on the full structure of the national accounts, E3ME is capable of producing a broad range of economic indicators. In addition there is range of energy and environment indicators. The following list provides a summary of the most common model outputs:

- GDP and the aggregate components of GDP (household expenditure, investment, government expenditure and international trade)
- sectoral output and GVA, prices, trade and competitiveness effects
- international trade by sector, origin and destination
- consumer prices and expenditures
- sectoral employment, unemployment, sectoral wage rates and labour supply
- energy demand, by sector and by fuel, energy prices
- CO_2 emissions by sector and by fuel
- other air-borne emissions
- material demands

This list is by no means exhaustive and the delivered outputs often depend on the requirements of the specific application. In addition to the sectoral dimension mentioned in the list, all indicators are produced at the national and regional level and annually over the period up to 2050.

E3ME as an E3 model

The E3 interactions

The figure below shows how the three components (modules) of the model - energy, environment and economy - fit together. Each component is shown in its own box. Each data set has been constructed by statistical offices to conform with accounting conventions. Exogenous factors coming from outside the modelling framework are shown on the outside edge of the chart as inputs into each component. For each region's economy the exogenous factors are economic policies (including tax rates, growth in government expenditures, interest rates and exchange rates). For the energy system, the outside factors are the world oil prices and energy policy (including regulation of the energy industries). For the environment component, exogenous factors include policies such as reduction in SO2 emissions by means of end-of-pipe filters from large combustion plants. The linkages between the components of the model are shown explicitly by the arrows that indicate which values are transmitted between components.

The economy module provides measures of economic activity and general price levels to the energy module; the energy module provides measures of emissions of the main air pollutants to the environment module, which in turn can give measures of damage to health and buildings. The energy module provides detailed price levels for energy carriers distinguished in the economy module and the overall price of energy as well as energy use in the economy.

The role of technology

Technological progress plays an important role in the E3ME model, affecting all three Es: economy, energy and environment. The model's endogenous technical progress indicators (TPIs), a function of R&D and gross investment, appear in nine of E3ME's econometric equation sets including trade, the labour market and prices. Investment and R&D in new technologies also appears in the E3ME's energy and material demand equations to capture energy/resource savings technologies as well as pollution abatement equipment. In addition, E3ME also captures low carbon technologies in the power sector through the FTT power sector model (see Section 2.2 or for more detail, Mercure, 2012).

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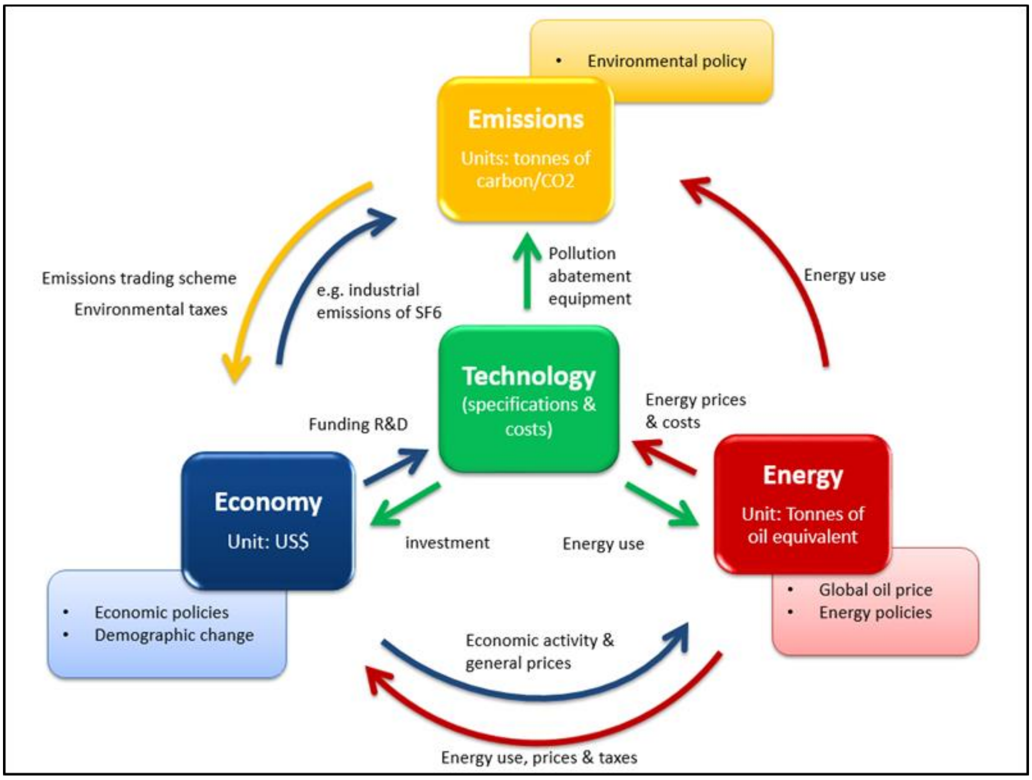
Figure 0.1: Interactions between emissions, economy and energy sectors



Treatment of international trade

An important part of the modelling concerns international trade. E3ME solves for detailed bilateral trade between regions (similar to a two-tier Armington model). Trade is modelled in three stages:

- econometric estimation of regions' sectoral import demand
- econometric estimation of regions' bilateral imports from each partner
- forming exports from other regions' import demands

Trade volumes are determined by a combination of economic activity indicators, relative prices and technology.

The labour market

Treatment of the labour market is an area that distinguishes E3ME from other macroeconomic models. E3ME includes econometric equation sets for employment, average working hours, wage rates and participation rates. The first three of these are disaggregated by economic sector while participation rates are disaggregated by gender and five-year age band.

The labour force is determined by multiplying labour market participation rates by population. Unemployment (including both voluntary and involuntary unemployment) is determined by taking the difference between the labour force and employment. This is typically a key variable of interest for policy makers.

Comparison with CGE models and econometrics specification

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E3ME is often compared to Computable General Equilibrium (CGE) models. In many ways the modelling approaches are similar; they are used to answer similar questions and use similar inputs and outputs. However, underlying this there are important theoretical differences between the modelling approaches.

In a typical CGE framework, optimal behaviour is assumed, output is determined by supply-side constraints and prices adjust fully so that all the available capacity is used. In E3ME the determination of output comes from a post-Keynesian framework and it is possible to have spare capacity. The model is more demand-driven and it is not assumed that prices always adjust to market clearing levels.

The differences have important practical implications, as they mean that in E3ME regulation and other policy may lead to increases in output if they are able to draw upon spare economic capacity. This is described in more detail in the model manual.

The econometric specification of E3ME gives the model a strong empirical grounding. E3ME uses a system of error correction, allowing short-term dynamic (or transition) outcomes, moving towards a long-term trend. The dynamic specification is important when considering short and medium-term analysis (e.g. up to 2020) and rebound effects[18] , which are included as standard in the model's results.

Key strengths of E3ME

In summary the key strengths of E3ME are:

- the close integration of the economy, energy systems and the environment, with two-way linkages between each component
- the detailed sectoral disaggregation in the model's classifications, allowing for the analysis of similarly detailed scenarios
- its global coverage, while still allowing for analysis at the national level for large economies
- the econometric approach, which provides a strong empirical basis for the model and means it is not reliant on some of the restrictive assumptions common to CGE models
- the econometric specification of the model, making it suitable for short and medium-term assessment, as well as longer-term trends

Applications of E3ME

Scenario-based analysis
Although E3ME can be used for forecasting, the model is more commonly used for evaluating the impacts of an input shock through a scenario-based analysis. The shock may be either a change in policy, a change in economic assumptions or another change to a model variable. The analysis can be either forward looking (ex-ante) or evaluating previous developments in an ex-post manner. Scenarios may be used either to assess policy, or to assess sensitivities to key inputs (e.g. international energy prices).

For ex-ante analysis a baseline forecast up to 2050 is required; E3ME is usually calibrated to match a set of projections that are published by the European Commission and the IEA but alternative projections may be used. The scenarios represent alternative versions of the future based on a different set of inputs. By comparing the outcomes to the baseline (usually in percentage terms), the effects of the change in inputs can be determined.

[18] Where an initial increase in efficiency reduces demand, but this is negated in the long run as greater efficiency lowers the relative cost and increases consumption. See Barker et al (2009).

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It is possible to set up a scenario in which any of the model's inputs or variables are changed. In the case of exogenous inputs, such as population or energy prices, this is straight forward. However, it is also possible to add shocks to other model variables. For example, investment is endogenously determined by E3ME, but additional exogenous investment (e.g. through an increase in public investment expenditure) can also be modelled as part of a scenario input.

Price or tax scenarios

Model-based scenario analyses often focus on changes in price because this is easy to quantify and represent in the model structure. Examples include:

- changes in tax rates including direct, indirect, border, energy and environment taxes
- changes in international energy prices
- emission trading schemes

Regulatory impacts

All of the price changes above can be represented in E3ME's framework reasonably well, given the level of disaggregation available. However, it is also possible to assess the effects of regulation, albeit with an assumption about effectiveness and cost. For example, an increase in vehicle fuel-efficiency standards could be assessed in the model with an assumption about how efficient vehicles become, and the cost of these measures. This would be entered into the model as a higher price for motor vehicles and a reduction in fuel consumption (all other things being equal). E3ME could then be used to determine:

- secondary effects, for example on fuel suppliers
- rebound effects[19]
- overall macroeconomic impacts

Table 1: Main dimensions of the E3ME model

	Regions	Industries (Europe)	Industries (non-Europe)
1	Belgium	Crops, animals, etc	Agriculture etc
2	Denmark	Forestry & logging	Coal
3	Germany	Fishing	Oil & Gas etc
4	Greece	Coal	Other Mining
5	Spain	Oil and Gas	Food, Drink & Tobacco
6	France	Other mining	Textiles, Clothing & Leather
7	Ireland	Food, drink & tobacco	Wood & Paper
8	Italy	Textiles & leather	Printing & Publishing
9	Luxembourg	Wood & wood prods	Manufactured Fuels
10	Netherlands	Paper & paper prods	Pharmaceuticals
11	Austria	Printing & reproduction	Other chemicals
12	Portugal	Coke & ref petroleum	Rubber & Plastics
13	Finland	Other chemicals	Non-Metallic Minerals
14	Sweden	Pharmaceuticals	Basic Metals
15	UK	Rubber & plastic products	Metal Goods
16	Czech Rep.	Non-metallic mineral prods	Mechanical Engineering
17	Estonia	Basic metals	Electronics
18	Cyprus	Fabricated metal prods	Electrical Engineering
19	Latvia	Computers etc	Motor Vehicles
20	Lithuania	Electrical equipment	Other Transport Equipment

[19] In the example, the higher fuel efficiency effectively reduces the cost of motoring. In the long-run this is likely to lead to an increase in demand, meaning some of the initial savings are lost. Barker et al (2009) demonstrate that this can be as high as 50% of the original reduction

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21	Hungary	Other machinery/equipment	Other Manufacturing
22	Malta	Motor vehicles	Electricity
23	Poland	Other transport equip	Gas Supply
24	Slovenia	Furniture; other manufacture	Water Supply
25	Slovakia	Machinery repair/installation	Construction
26	Bulgaria	Electricity	Distribution
27	Romania	Gas, steam & air cond.	Retailing
28	Norway	Water, treatment & supply	Hotels & Catering
29	Switzerland	Sewerage & waste	Land Transport etc
30	Iceland	Construction	Water Transport
31	Croatia	Wholesale & retail MV	Air Transport
32	Turkey	Wholesale excl MV	Communications
33	Macedonia	Retail excl MV	Banking & Finance
34	USA	Land transport, pipelines	Insurance
35	Japan	Water transport	Computing Services
36	Canada	Air transport	Professional Services
37	Australia	Warehousing	Other Business Services
38	New Zealand	Postal & courier activities	Public Administration
39	Russian Fed.	Accommodation & food serv	Education
40	Rest of Annex I	Publishing activities	Health & Social Work
41	China	Motion pic, video, television	Miscellaneous Services
42	India	Telecommunications	Unallocated
43	Mexico	Computer programming etc.	
44	Brazil	Financial services	
45	Argentina	Insurance	
46	Colombia	Aux to financial services	
47	Rest Latin Am.	Real estate	
48	Korea	Imputed rents	
49	Taiwan	Legal, account, consult	
50	Indonesia	Architectural & engineering	
51	Rest of ASEAN	R&D	
52	Rest of OPEC	Advertising	
53	Rest of world	Other professional	
54	Ukraine	Rental & leasing	
55	Saudi Arabia	Employment activities	
56	Nigeria	Travel agency	
57	South Africa	Security & investigation, etc	
58	Rest of Africa	Public admin & defence	
59	Africa OPEC	Education	
60		Human health activities	
61		Residential care	
62		Creative, arts, recreational	
63		Sports activities	
64		Membership orgs	
65		Repair comp. & pers. goods	
66		Other personal serv.	
67		Hholds as employers	
68		Extraterritorial orgs	
69		Unallocated/Dwellings	

Source(s): Cambridge Econometrics.

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