BRAIN-Energy: Bounded Rationality Agents Investments model

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1. Overview

This document provides a description of BRAIN-Energy (Bounded Rationality Agents INvestments model), of its key equations, calibration data, actors (Market players and institutional actors) and characteristics. It also provides an explanation about the market players' investment process, providing the key mathematical formulations.

BRAIN-Energy is implemented in the open-source software environment Netlogo (Wilensky, 1999), a specific software for agent-based and system dynamics modelling: https://ccl.northwestern.edu/netlogo/ It is calibrated to 2012 as a base year, and it proceeds to 2050 in yearly time-steps. BRAIN-Energy's yearly resolution is justified by the fact that the investment decisions of the market players and the interactions between market players and the institutional agents – the core of BRAIN-Energy's analysis - are better captured on an annual basis.

BRAIN-Energy is an agent-based model (ABM) of electricity generation and investments. It focuses on the electricity supply sector, and it has been calibrated to the UK, German and Italian electricity supply sectors. BRAIN-Energy's aim is to study how heterogeneous agents with bounded-rationality and with heterogeneous characteristics, whose investment choices are influenced by the past (hence are path-dependent), and their interactions impact future decarbonisation pathways of the electricity sector to 2050.

BRAIN-Energy aims to address a gap in existing energy-modelling literature, where most studies assume homogeneous and perfectly rational agents, and lack attention to the actors' heterogeneity and bounded-rationality (Bergek et al., 2013; Iychettira et al., 2017; Wüstenhagen and Menichetti, 2012).

Case studies are the UK, the German and the Italian electricity markets.

2. Brief description and model flow

BRAIN-Energy is an agent-based model of electricity generation and investment. Its strength and novelty lies in the model's sophisticated representation of agent behaviour.

BRAIN-Energy gives a stylised representation of the UK, German and Italian electricity sectors in terms of generation technologies, installed capacity, actors (market players and institutional agents), policies in the energy sector and climate change targets. For each country the market players have been clearly defined based on extensive literature search.

BRAIN-Energy is based on evolutionary economics and its main building blocks (Safarzynska and Van den Bergh, 2010; Nelson and Winter, 1982). Agents in BRAIN-Energy have *bounded rationality*, they are *heterogenous* (which leads to diversity in the model, another important concept in evolutionary economics), and their investment choices are influenced by the past, which leads them to being *adaptive* and *path-dependent*. Moreover, *imitation*, hence *learning*, influences agents' investment decisions. This leads to *selection of the best strategies*, even though this process is not perfect due to agents' bounded-rationality. Finally, the investment choices of the market players and their outcomes *co-evolve* with the surrounding policy environment and governance structure.

Figure 1 illustrates BRAIN-Energy's yearly flow and how it iterates through the different steps.

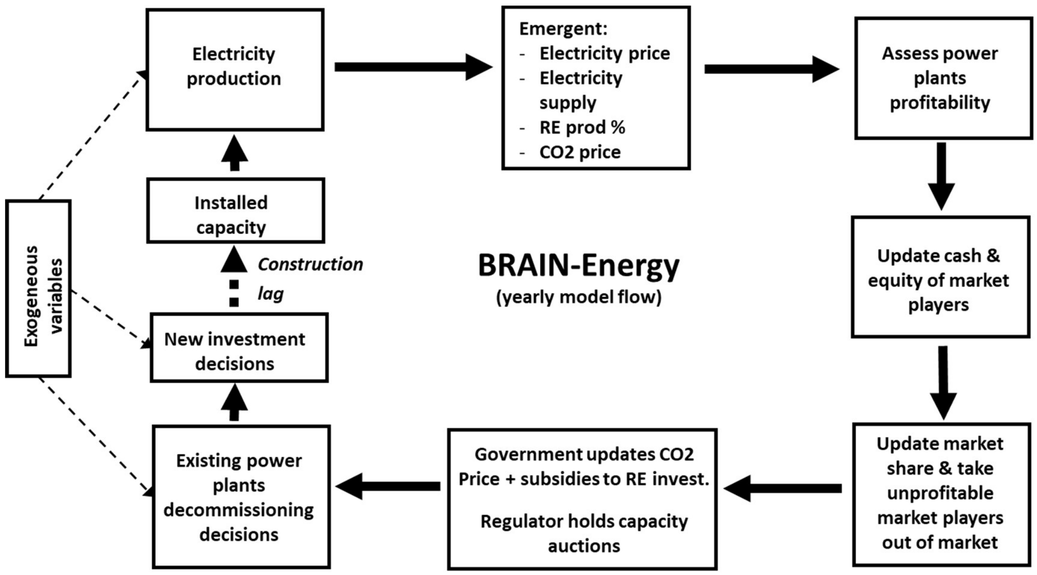

Figure 1 - BRAIN-Energy's flow

Each year market players take short-term operational decisions (electricity production from their stock of assets), and bid electricity into the market. As a result of their electricity sales, the yearly electricity price is created (section 5), as well as the electricity supply curve (section 5) and the CO2 emissions from the power sector (section 5). Based on their electricity sales and on the electricity price market players assess the profitability of their stock of assets and their financial position is updated. The market players' financial position then constrains (or encourages) their long-run investment decisions.

As a next step, the government agent checks the amount of CO2 emissions (or emission intensity) produced by the power sector. If the interim decarbonisation targets are not met, the government agent can adjust the prevailing CO2 price (Table 10). The regulator agent also intervenes in the market to manage eventual supply gaps by enforcing capacity auctions (in the UK and Italian versions of BRAIN-Energy only). ***Therefore, the policy changes which the institutional agents (the government and the regulator) enforce in BRAIN-Energy are endogenous, and co-evolve with the emergent techno-economic properties of the sector through the years.***

Finally market players take decisions about decommissioning unprofitable assets (section 6) and decide about new investments (section 6). Newly committed investments start being operational after a planning- and construction lag, and ***the resulting generation mix is, therefore, an emergent result of the investment and decommissioning decisions of the market players.***

3. Data and calibration

Table 1 summarises the main exogenous variables and outcomes of BRAIN-Energy. Section 3.1 provides details about calibration data for the UK model, while section 3.2 provides details about data used in the German model, and section 3.3 details data used in the Italian model.

Exogenous variables	Outcomes
• Electricity demand • Fuel costs • Capital costs of technologies • Fixed and variable operational and maintenance (O&M) costs of technologies • CO2 price (only in the scenarios where the government agents doesn't adjust the CO2 price, and in all other scenarios only the "no-increase trajectory, see Table 2)	• Aggregated and yearly capital investments (by technology and by market player) • Electricity price • Electricity production (amount and share of production by technology) • Installed capacity (total and split by technology) • Average and peak supply-demand gaps • CO2 emissions from the power sector and carbon intensity of electricity generation • Market shares of the market players

Table 1- BRAIN-Energy's exogenous variables and outcomes

3.1 UK model

The UK model is calibrated to 2012 using official government statistics (BEIS, 2016). Active generation technologies in the UK model are based on the existing generation fleet at the base year 2012 (BEIS, 2016) and are detailed in Table 2.

Technology	GW
Gas CCGT	35
Coal	30
Nuclear	9
Onshore wind	6
Offshore wind	3
PV	2
Hydro	4
Biomass	3
Peaking plants (e.g. oil)	2

Table 2 - Installed capacity in UK BRAIN-Energy (source: BEIS, 2016)

The technical and operational performance of the different technologies is expressed in terms of variable operational costs (fuel costs), carbon costs, and fixed operations and maintenance costs (O&M costs) per unit of electricity produced. O&M costs are based on the fixed operations and maintenance costs components of the levelized cost of electricity production (LCOE) of each technology (BEIS, 2016b). Other technical parameters of the generation plants, such as load factors, lifetime and emission intensity, are summarised in Table 3.

Technology	Average load factor	Lifetime	Emission intensity (gCO2/kWh)
Gas CCGT	93%	25 years	365
Coal	90%	30 years	907
Nuclear	90%	60 years	
Onshore wind	32%	24 years	
Offshore wind	43%	23 years	
PV	11%	25 years	
Hydro	40%	35 years	
Biomass	84%	25 years	
Peaking plants (e.g. oil)	22%	25 years	

Table 3 - Technical power plant data in UK version of BRAIN-Energy (source: BEIS, 2016b)

Fuel costs of gas and coal are based on historical gas and coal prices found in the BEIS (2016a) report. They can be found in Appendix A. Assumptions about fuel costs future evolution reflect the UK's government view and are based on the BEIS (2016a) "Reference scenario" estimates, because this scenario is based on central estimates of fossil fuel prices and economic growth for the UK, which are based on all agreed (hence also "planned" policies) and existing policies as of BRAIN-Energy's calibration year.

Existing generation technologies also provide future investment options for electricity generation in BRAIN-Energy, except for hydro which capacity is assumed to remain constant through the years.
Each generation technology has an associated capital cost (Table 4) expressed in EUR/kW (which is converted into £/kW in the UK version of BRAIN-Energy). The same technology capital cost data has been used in the UK, German and Italian models. Data about technologies' capital costs and their expected evolution to 2050 in BRAIN-Energy is based on data from DIW's Current and Prospective Costs of Electricity Generation until 2050 report (DIW, 2013), and has been double-checked against historical data from IRENA (2018).

Technology	2012	2015	2020	2025	2030	2035	2040	2045	2050
Gas CCGT	400	400	400	400	400	400	400	400	400
Coal	1,800	1,800	1,800	1,800	1,800	1,800	1,800	1,800	1,800
Nuclear	6,000	6,000	6,000	6,000	6,000	6,000	6,000	6,000	6,000
Onshore wind	1,300	1,269	1,240	1,210	1,182	1,154	1,127	1,101	1,075
Offshore wind	3,000	2,868	2,742	2,621	2,506	2,396	2,290	2,189	2,093
PV	1,560	950	750	675	600	555	472	448	425
Biomass	2,500	2,424	2,350	2,278	2,209	2,141	2,076	2,013	1,951
Peaking plants (e.g. oil)	400	400	400	400	400	400	400	400	400

Table 4 - Technologies capital costs in UK, German and Italian versions of BRAIN-Energy in EUR/kW (source: DIW, 2013)

Carbon costs (Figure 4) for conventional generation technologies in the UK model comprise the EU ETS price plus the Carbon Support Price component of the Carbon Price Floor (CPF), and are based on historical data found in the BEIS (2016a) report also in the "Reference" scenario as for fuel prices. The "no-increase" CO2 price trajectory, which is the prevailing CO2 price over which the government agent can increase the CO2 price when interim carbon budgets are not met (the different CO2 price trajectories which the government agents can apply are explained in section 4.2 in Table 10), is modelled according to the "Reference " scenario in the BEIS (2016a) report. The different CO2 price trajectories are shown in Figure 2.

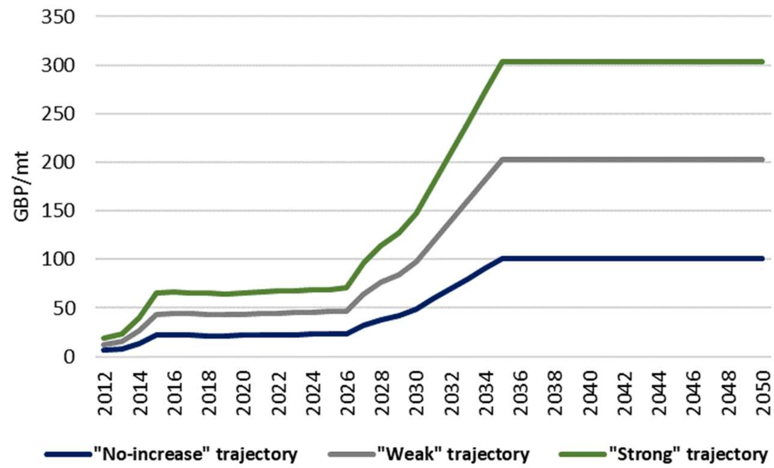

Figure 2 - CO2 price trajectories in UK BRAIN-Energy

Electricity demand (an exogenous variable in BRAIN-Energy) is calibrated until 2016 on historical half-hourly National Grid data. Assumptions about future demand evolution are based on the National Grid's Future Energy Scenarios 2016 report (National Grid, 2016). These scenarios have been chosen for the calibration of future electricity demand, in order to be consistent with historical data, and because of their level of detail and disaggregation until 2050. Figure 3 shows the calibration of electricity demand in the UK version of BRAIN-Energy.

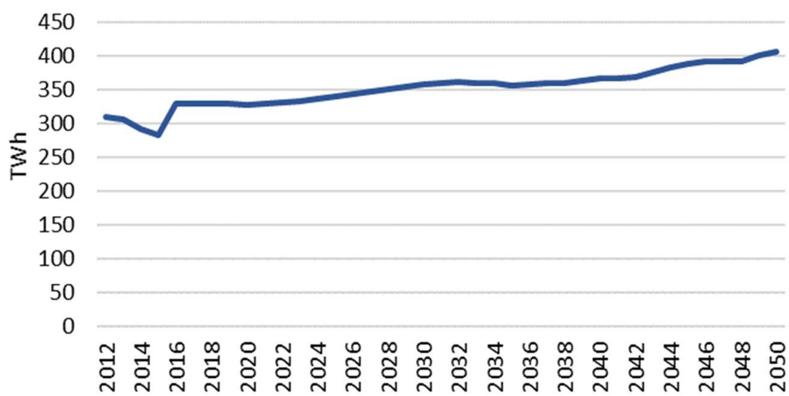

Figure 3 - Electricity demand in UK BRAIN-Energy

3.2 German model

The German model has also been calibrated to 2012 as a base year. Active generation technologies and installed capacity at 2012 is based on data from the Bundesnetzagentur[1] and are summarised in Table 5.

[1] https://www.bundesnetzagentur.de/.../Kraftwerksliste/Kraftwerksliste_2018_1.xlsx?__

Technology	GW
Gas CCGT	29.5
Lignite	22
Hard coal	25
Nuclear	12
Onshore wind	31
Offshore wind	0.6
PV	33.5
Hydro	14.5
Biomass	6
Peaking plants (e.g. oil)	4

Table 5 - Installed capacity in German BRAIN-Energy (source: Bundesnetzagentur Kraftwerkliste, 2018)

As it is for the UK model these technologies, except for coal and lignite plants which are due to be phased out according to European legislations and to plans of the German government, also provide future investment options. Nuclear is not a feasible investment option in the German version of BRAIN-Energy, as in 2011, following the Fukushima nuclear disaster, the German parliament with the 13th Amendment to the Atomic Energy Act set fixed dates for the phase-out of existing nuclear power stations.

Technical power plant data, such as fixed O&M costs for different technologies are based on data from DIW (2013). Load factors for the different generation technologies in the German model are assumed to be the same as in the UK model (Table 3), and so is the technical lifetime of the power plants. The emission intensity of conventional power plants in the German version of BRAIN-Energy is detailed in Table 6.

Technology	Emission intensity (tCO2/MWh)
Gas CCGT	0.73
Lignite	0.33
Hard coal	0.94

Table 6 – Emission intensity of conventional power plants in Germany (source: Prognos, 2014)

Historical fuel prices for gas and coal have been calibrated using data from the BmWi Energiedaten. Fuel costs to 2050 are based on Prognos (2014). Details are provided in Appendix B.

As it is for the UK version of the model, capital costs for the different conventional and renewable generation technologies are based on the DIW (2013) as in Table 4.

Historical CO2 prices in the German model (Figure 4) (in the "no-increase" CO2 price trajectory), which correspond to the value of the EUA certificates in the EU ETS scheme, are based on data from BMWi Energiedaten database[2] (which is based on historical monthly average data from the EEX Exchange). The evolution of CO2 prices to 2050 (in the "no-increase" CO2 price trajectory) is modelled according to assumptions found in the Prognos (2014) report, which assumes a value of EUR 40/Mt CO2 (in real prices) in 2030 in the "Referenzprognose" scenario, and of EUR 76/Mt CO2 (real prices) in 2050 in the "Trendszenario" (Figure 4).

[2] https://www.bmwi.de/Redaktion/DE/Binaer/Energiedaten/energiedaten-gesamt-xls.html

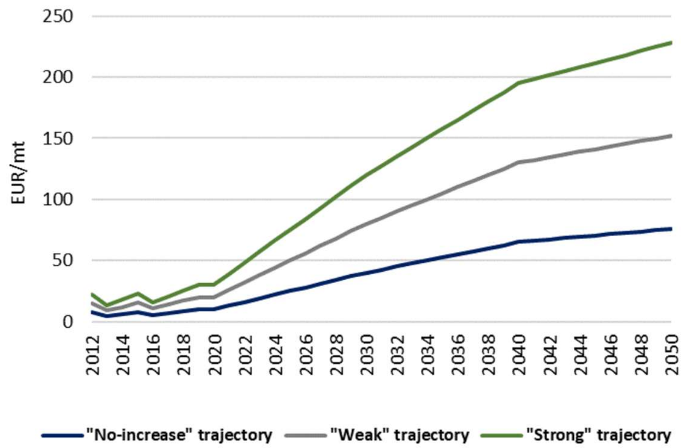

Figure 4- CO2 price trajectories in German (and Italian) BRAIN-Energy

Historical electricity demand for Germany (Figure 5) has been calibrated using half-hourly data from the Open Power System Data Platform[3], and on data from AG Energiebilanz[4]. The forecasted evolution of electricity demand is based on the future scenarios' data in the Prognos (2014) report (Figure 5).

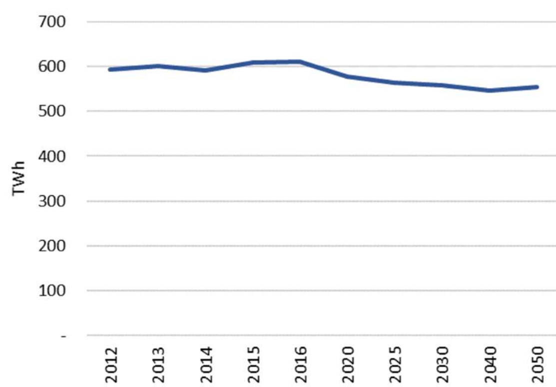

Figure 5 - Electricity demand in German BRAIN-Energy

3.3 Italian model

Based on data from Terna (2012) active generation technologies and their installed capacity at the base year are detailed in Table 7.

Technology	GW
Gas CCGT	63.8
Coal	8.5
Onshore wind	8.1
PV	16.6
Hydro	22.2
Biomass	3.8
Peaking plants (e.g. oil)	9

Table 7- Installed capacity in Italian BRAIN-Energy (source: Terna, 2012)

[3] https://data.open-power-system-data.org

[4] https://ag-energiebilanzen.de/10-0-Auswertungstabellen.html

The different technologies' technical and operational data, such as fixed O&M costs, is obtained from the same source as in the German model to make the models comparable. Also emission intensity of power plants has been assumed to be the same as in the German model in the Italian model (Table 6). In contrast, the operational load factors of the generation technologies are obtained from RSE Colloquia (2017) (Table 8).

Capital costs of the generation technologies are the same as in the UK and in Germany (Table 4).

Moreover, historical fuel costs for Italy are based on data from Gestore del Mercato Electtrico (GME), while their future evolution to 2050 has been assumed to be the same as in the German model. This has been done because reliable data on future gas prices in Italy could not be obtained, and because of the rather small differences in historical prices between the two countries.

Historical CO2 prices, and assumptions about their future trajectory, are the same as in the German model and based on the same sources, as Italy also participates in the EU ETS scheme, and the carbon price is similarly based on the market value of the EUA certificates (Figure 4).

Electricity demand in the Italian version of BRAIN-Energy (Figure 6) has been calibrated on half-hourly data from Terna and the Gestore del Mercato Electtrico (GME), while assumptions about electricity demand's future evolution are based on "Scenari della domanda electtrica in Italia" (Terna, 2016) and on Terna (2018).

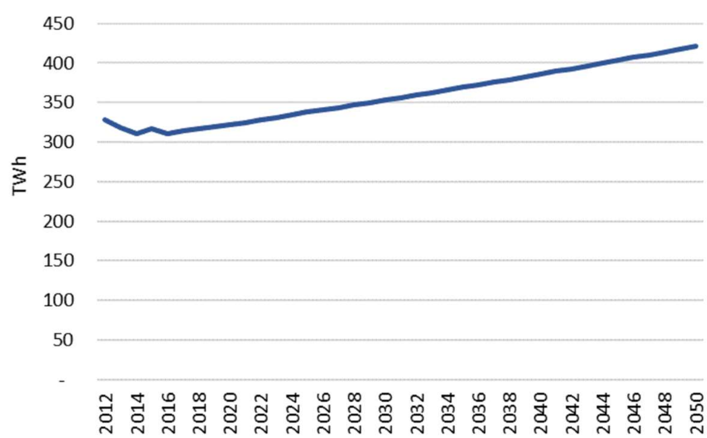

Figure 6 - Electricity demand in Italian BRAIN-Energy (source: GME, Terna 2016, Terna 2018)

4. Actors and characteristics

4.1 Overview of types of market players

7 different types of market players are modelled in BRAIN-Energy (Table 8). Table 9 shows which players (and how many of each type) invest in each country's market.

Market players	Description
Incumbent utilities	Main players in the electricity sector, whose main business is electricity generation. Some are vertically integrated companies, which also own the supply business.
Independent power producers (IPPs)	Project developers, which develop, own, operate new generation assets, and eventually then sell these on. IPPs are not vertically integrated as incumbent utilities.
New-entrants	New-type of electricity generators (e.g. IT companies entering the electricity market). Their main business is not electricity generation. Not existent at the beginning of the simulations in BRAIN-Energy.
Municipal utilities	Directly or indirectly owned by a municipality or city, and operate only in their regions, to which they are strategically committed.
Institutional investors	Institutional investors (such as pension funds and insurance companies) are financial institutions that manage funds on behalf of others.
"Civic" sector players	Households. They invest in small scale renewable energy facilities, to cover self-consumption, and might sell surplus locally.

Table 9 – Types of market players in BRAIN-Energy

Type of market player	UK	Germany	Italy
Incumbent utilities	4	3	3
IPPs	2	2	2
New-entrants	None at 2012 – up to *n* through to 2050	None at 2012 – up to *n* through to 2050	None at 2012 – up to *n* through to 2050
Municipalities	N/a	2	N/a
Institutional investors	N/a	2	2
"Civic" sector actors	N/a	8	6

Table 9 - Market players in UK, Germany and Italy

"Civic" sector actors (Hall et al., 2016) are households in BRAIN-Energy. A household market player in BRAIN-Energy is an aggregation of 1,000 households, to reflect the fact that the average household investment in PV in Germany and Italy is 10 kW (CPI, 2012; GSE, 2016) and the minimum investment size in PV in BRAIN-Energy is 10 MW.

In BRAIN-Energy market players are heterogeneous based on: 1) the type of organisation, 2) their characteristics. Their characteristics consists of the following elements:

- Aim
- Technological preferences
- Foresight
- Number of years before unprofitable assets are closed down
- Cost of capital

4.2 Institutional agents (government and regulator)

The government agent in BRAIN-Energy is responsible for making sure that the legally binding CO2 reduction targets are met, and that the low-carbon transition of the electricity sector is on track to meet the interim carbon budgets.

The level of the government activity and its commitment to meet climate change targets is measured by the degree to which the government agent increases the carbon price over the prevailing “no-increase” trajectory when the interim carbon budgets are not met. There are three CO2 price trajectories which the government agent can apply, which are explained in Table 10. If in between carbon budgets the carbon intensity of electricity generation (or the share of electricity produced through renewable sources) falls below the desired level, the government decreases the CO2 price again to the “no-increase” trajectory

CO2 price trajectory	Description and calibration
“No-increase”	This is the prevailing CO2 price at the onset of all scenarios in BRAIN-Energy. **UK:** • Historical: EU ETS + Carbon Price Floor according to the “Reference” scenario in BEIS (2016) • Future: “Reference” scenario in BEIS (2016) **Germany and Italy:** • Historical: EU ETS (BmWi Energiedaten database[5]) • Future: “Referenzprognose” scenario and “Trendszenario” (Prognos, 2014)
“Weak”	This trajectory represents a weak commitment by the government to meet decarbonisation targets. Under the “weak” trajectory, when interim carbon budgets are not met, the government increases the CO2 price by 100% over the “no-increase” trajectory .
“Strong”	This trajectory represents a strong commitment by the government to meet decarbonisation targets. Under the “strong” trajectory, when interim carbon budgets are not met, the government increases the CO2 price by 200% over the “no-increase” trajectory

Table 10- CO2 price trajectories in BRAIN-Energy

The frequency of the carbon budgets can be found in Table 11 for the UK, Table 12 for Germany and Table 13 for Italy.

Year	Carbon intensity of power generation
2020	250 gCO2/kWh
2025	200 gCO2/kWh
2030	100 gCO2/kWh
2035	50 gCO2/kWh
2040	25 gCO2/kWh
2045	15 gCO2/kWh
2050	Near-zero

Table 11- Carbon budgets in UK BRAIN-Energy

[5] https://www.bmwi.de/Redaktion/DE/Binaer/Energiedaten/energiedaten-gesamt-xls.html

Year	Share of renewables in electricity production
2020	20%
2025	45%
2035	60%
2045	70%
2050	>=80%

Table 12 - Carbon budgets in German BRAIN-Energy

Year	Share of renewables in electricity production
2020	20%
2030	55%
2040	70%
2050	>=80%

Table 13 - Carbon budgets in Italian BRAIN-Energy

The government agent also subsidises investments in new renewable generation assets either through Contracts for Difference (CfDs) in the UK, or through feed-in tariffs (FITs) in Germany and in Italy.

CfD auctions take place every three years, and winners of the auctions are paid the difference between an auction's strike price and the prevailing market price for 15 years, hence providing stability and predictability to investors' revenues for 15 years. In BRAIN-Energy the strike price (expressed in MWh) which agents bid into the market is calculated as the price which allows them to recover capital expenditures for a given project *p* ($CAPEX\ p$), interest costs on the loan raised to finance the project *p* (r), and O&M, fixed and variable costs associated to the expected level of electricity generation from project *p* in a given year *t* ($g_{p,t}$) , hence to have an net present value (NPV) equal to zero.

$$SP_{x,p,t} = \frac{\left(\frac{CAPEX_p}{l_p} \times (1 + r)\right) + c_{p,t}}{g_{p,t}}$$

where:
$SP_{x,p,t}$ is the strike price required by generator or investor *x* for plant *p* at time *t*
l_p is the lifetime of plant *p*
$c_{p,t}$ is the expected cost of generation of plant *p* in year *t* based on fixed, O&M and variable costs

In the German and Italian versions of BRAIN-Energy the government agents use Feed-in-tariffs (FITs), according to the laws in these two countries. In BRAIN-Energy FITs are modelled as fixed price which market participants receive on their low-carbon investments for 15 years ahead. Hence, when generators and investors calculate the expected profitability of future investments (as described later in point 6.a), instead of using the expected electricity price they based their calculation on the level of the FITs which the government agents provide for each technology.

The regulator agent in BRAIN-Energy manages security of supply through a capacity market in the UK and in the Italian models. The way the capacity market works in the UK version of BRAIN-Energy is represented by the fact that the regulator agent, who also has bounded-rationality, forecasts every year the maximum potential electricity production at *t+4* ($maxs_{t+4}$) by estimating the maximum potential electricity production of all active power plants with plant life of at least or greater than *t+4.* If the maximum potential electricity production at *t+4* ($maxs_{t+4}$) is lower than peak demand at year *t+4*, then the regulator agent sets a capacity auction into place at year *t* with capacity to be delivered at *t+4*. The capacity to be auctioned (CA_t) is then:

$$CA_t = PeakDemand_{t+4} - maxs_{t+4}$$

In BRAIN-Energy, the capacity market functions for new capacity investments only and is modelled following Hach et al. (2015). The price that market players bid into the market is the annual payment from which a negative NPV turns to zero ($CP_{p,t}$) . If the NPV of a project is already greater than zero, than generators and investors bid zero into the capacity auction.

$$CP_{p,t} = \max(0; -NPV)$$

where:

$CP_{p,t}$ is the annual capacity payment for plant *p* at time *t* which agents participating into the capacity auction bid into the market. It is capped at £75/kW a year in accordance with regulation in the UK market.

5. Power sector operations

Electricity demand, an exogenous variable in BRAIN-Energy, has been divided into average yearly day demand and average yearly night demand based on historical data, to account for diurnal variations in electricity load. The sources used were provided in sections 3.1 for UK, 3.2 for Germany a 3.3 for Italy.

A yearly peak demand in GW has been defined, which is calculated as the yearly average day demand multiplied by the peak factor. For all the three countries, the peak factor (PF) has been calibrated on historical observations of the absolute yearly peak electricity demand in the UK, Germany and Italy, and is defined as a percentage of the average yearly day demand. Peak factors used in the three case studies are reported in Table 14.

	% of yearly average day demand
UK	125%
Germany	130%
Italy	150%

Table 14 – Peak factors (source: same sources as for electricity demand)

The peak factor (PF) is assumed to be constant through the years from 2012 to 2050.

$$PeakDemand_t = AverageYearlyDayDemand_t \times PF$$

To account for the intermittency of renewable generation assets, their installed capacity has been de-rated by their load-factor. Moreover, renewable plants in this model have a declining “contribution to peak”, which means that the marginal contribution of each new renewable generation asset in meeting peak demand is declining the more renewables are installed in the system.

Electricity production bidding strategy (b_t) of market players:

$$b_t = f(SRMC_{p,t,}, ep_{p,t})$$

Where:

$SRMC_{p,t,}$ is the short-run marginal cost of plant p at time t
$ep_{p,t}$ is the potential available production capacity of power plant *p* in MWh at time *t*
Short-run marginal cost of generators:

$$SRMC_{p,t} = \frac{(p_{f,t} + p_{CO2,t}) \times ep_t + fc_{p,t}}{ep_{p,t}}$$

where:
$p_{f,t}$ is the price of fuel *f* at time *t* for a MWh of electricity, $p_{CO2,t}$ is the CO2 price at time *t* for a MWh of electricity, ep_t is the potential available production of plant *p* at time *t* in MWh, $fc_{p,t}$ are the fixed O&M costs for plant *p* at time *t*

The wholesale electricity price at year *t* (*p t*) is equal to the short run marginal cost of the last and most expensive bid accepted into the market, which is required to meet electricity demand in that year.

Total CO2 emissions and carbon intensity of the power sector: At the end of each year, based on the production mix resulting from the merit order, hence on the share of electricity produced through renewable sources and through conventional sources, total emissions in the power sector ($TotCO2_t$) at time *t* and carbon intensity of electricity generation (CI_t) at time *t* are calculated.

$$TotCO2_t = \sum_x^n ((s_{p,day,t} + s_{p,night,t}) \times EI_p)$$

$$CI_t = \frac{TotCO2_t}{\sum_x^n (s_{p,day,t} + s_{p,night,t})}$$

where:
$s_{p,day,t}$ total day electricity production of power plant *p* at time *t*, $s_{p,night,t}$ total night electricity production of power plant *p* at time *t*, EI_p is the emission intensity of plant p, n is number of active power plants at time *t*

6. Investment process

In BRAIN-Energy the investment choices of the market players co-evolve with the policy dimension and the governance structure. This is illustrated in Figure 7.

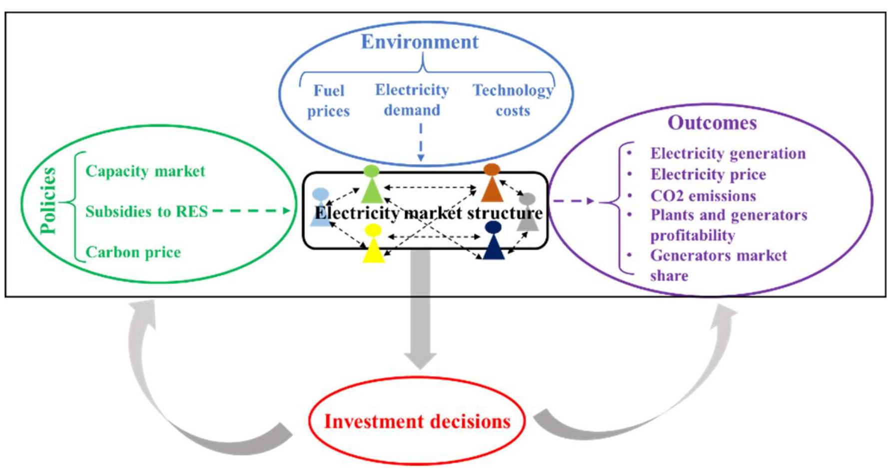

Figure 7 - Investment process in BRAIN-Energy and co-evolution with other dimensions

6.1 Economic criteria in investment decisions

Market players in the power market take yearly decisions to decommission unprofitable power plants, reassess the profitability of prior investments and take decisions about building new power stations. Such strategic decisions are taken by each market player independently and sequentially one after the other.

Investment choices come after the operational activities of each market player, as they also depend on the amount of revenues generated by their core business of electricity production. Each market player finances part of the capital investment costs for new power stations from own resources (cash generated from operating activities), and the remaining part through debt taken by banks at a market player's specific cost.

Every year, all market players evaluate the potential future profitability of each generation technology in which they are willing and able to invest given their technology preferences, by calculating its net present value (NPV) up to a future reference year n years ahead. The value of n depends on each market player's foresight. As market player have myopic foresight and don't have perfect information about the future, their NPV calculations are based on their own micro-economic expectations and estimations about future electricity demand, fuel and technology prices, and cash-flow from future potential investment technologies.

Operating cash-flow ($CFop_p$) and NPV calculations:

$$CFop_p = \sum_{y=t}^{n} \frac{\left(ep_{p,t} \times p_{exp,t}\right) - (\left(vc_{f,c,p,t} \times ep_{p,t}\right) + fc_{p,t}}{(1+r)^y}$$

$$NPV_p = CFop_p - (\frac{CAPEX_{p,t}}{l_p} \times n)$$

Where:

$ep_{p,t}$ is the expected production of plant *p* at year *t*

$p_{exp,t}$ is the electricity price which each actor expects at time *t*

$vc_{f,c,p,t}$ are the variable costs of plant *p* as a function of fuel and carbon costs at time *t*

$fc_{p,t}$ are the fixed costs of plant *p* at time *t*

r is the interest rate that market players pay on their liabilities

$CAPEX_{p,t}$ is the project capital cost for generation technology *p* at time

If NPV is greater than zero, market players select the investment option with the highest return on investment (ROI).

Institutional investors (in the German and Italian versions of BRAIN-Energy) are assumed to invest directly into projects, and not through equity or debt of other companies (Blyth et al., 2015; CPI, 2012), and use the same investment calculations and process explained above.

"Civic" sector actors, instead, use a different process to evaluate future investment options. In fact, households (which can be found in both the German and the Italian model calculate the economic utility from future investments based on the length of the payback period, which is given by the year when the NPV of the new investment passes from being negative to being positive. This is based on Palmer et al. (2015) as this study is specifically focused on studying the adoption of solar PV between households in Italy.

6.2 Path-dependency in investment decisions

Path-dependency in investment choices in BRAIN-Energy is represented by the fact that:

- Market players' investment choices are constrained by the past performance of existing plants and investments, which dictate a market player's financial constraints. Hence, investment choices are adaptive and path-dependent. Learning from own successful past behaviour and investments is reflected in a market player's growing profit and improving financial situation. Hence, learning-by-doing and accumulation of knowledge in BRAIN-Energy lead to growing market shares and ability to commit new investments.

- Market players learn from their own unsuccessful past investments. After five years that a new plant started operations, market players assess its profitability every year. If at any given year a plant's cumulative profits over the previous five years defined as:

$$\sum_{y=t}^{n} PF_{p,t} = (prod_{p,t} \times p_t) - totCost_{p,t}$$

  are lower than the 5-yearly share of the new plant's total capital cost ($\frac{CAPEX_p}{l_p} \times n$) then the new investment is flagged as unprofitable.

  Where:
  l_p is the lifetime of plant p,
  $prod_{p,t}$ is the electricity production of plant p at year t,
  p_t is the electricity price at year t,
  $totCost_{p,t}$ comprise variable and fixed production costs and yearly capital costs.

  If the number of years during which the new plant is unprofitable in a row is greater than the number of years a market player is willing to absorb losses for, then it is shut down. A market player will only invest in the same technology when and if it becomes profitable again. This means that, if at any time the technology's NPV calculation is greater than zero, and if the ROI is equal or greater than the capital cost of the market player plus a threshold α which differs by type of market player, the market player will invest again in this technology. Thresholds α have been calibrated based on the wider characteristics and behaviours of the market players drawn from the literature. Threshold α can be between $1 \leq \alpha \leq 2$:

  - new-entrants and independent power producers: α = 1
  - institutional investors and incumbent utilities: α = 1.5
  - municipal utilities: α = 2

6.3 Imitation in investment decisions

In BRAIN-Energy investment choices are also influenced by the successful investments of the other market players.

"Civic" sector market player, such as households, can only imitate other players in the "civic" sector. All other agents can imitate each other, excluding "civic" sector players.

The way that imitation works in BRAIN-Energy is based on the evolutionary economics model of imitation proposed by Nannen and Van den Bergh (2010). As in Nannen and Van den Bergh (2010) in BRAIN-Energy agents have bounded-rationality, and the only information which they have available are the investment strategies of the other agents and their expectations about future technologies capital costs, fuel costs and electricity prices. Agent *a* in BRAIN-Energy measures the outcomes of the investment strategies of the other agents in terms of growth or decline of their market share, hence they believe that there is a link between investment strategies and development of the market share. Agent *a* also assess the investment strategies of the other players' in terms of early closures due to unprofitability of their new investment. If an agent's *x* market share (MS_x) is growing compared to the previous year, hence if $MS_{x,t+1} > MS_{,t}$, agent *a* chooses to imitate the agent *x* whose market share grew the most at year *t+1*, and who didn't close down any new power stations at year *t+1* due to unprofitability. Among the new investments of the agent *x* which agent *a* decides to imitate (given his technology preferences), agent *a* chooses to imitate investments in the generation technology with the highest expected ROI based on its own myopic expectations (or the shortest pay-back period for "civic" sector actors) and invests in that generation technology. This is because agent *a* doesn't have perfect information about which exact power plant or generation technologies caused the imitated agent's market share to increase between *t* and *t+1*.
As imitation is not a perfect process and errors can take place during the imitation process, imitation can lead to the creation of a number of diverse successful or unsuccessful investment strategies.

References

BEIS (2016) "Digest of UK Energy Statistics (DUKES) 2016 Chapter 5 Electricity"

BEIS (2016a), "Updated Energy and Emissions projections 2016"

BEIS (2016b), "Electricity Generation Costs"

Bergek, A., Sundberg, G. Mignon, I. (2013) "Who invests in renewable energy production? Empirical evidence and suggestions for further research", *Energy Policy*, 568--581.

DIW (2013), "Current and Prospective Costs of Electricity Generation until 2050", DIW Berlin (2013)

Global Capital Finance (2014), "The European Renewable Energy Investor Landscape", Global Capital Finance and Clean Energy Pipeline

Hall et al. (2016), "Financing the civic energy sector: How financial institutions affect ownership models in Germany and the United Kingdom", *Energy Research & Social Science* (2016), 5--15.

Hermelink and De Jager (2015), "Evaluating our future: The crucial role of discount rates in European Commission energy system modelling", The European Council for an Energy Efficient Economy (eceee) & Ecofys (2015)

HM Treasury (2011), "The Green Book: Appraisal and Evaluation in Central Government"

IEA/IRENA (2017), "Perspectives for the Energy Transition: Investment needs for low-carbon energy system", IEA/OECD and IRENA publishing

Iychettira , K., Hakvoort, R., Linares, P., De Jeu, R. (2017), “Towards a comprehensive policy for electricity from renewable energy: Designing for social welfare”, Applied Energy, 187: 228-242

Nannen and Van den Bergh (2010), “Policy instruments for evolution of bounded rationality: Application to climate and energy problems", *Technological Forecasting and Social Change* (2010), 76--93.

Nelson and Winter, 1982 "An Evolutionary Theory of Economic Change", Belknap Harvard (1982).

Palmer, J., Sorda, G., Madlener, R. (2015) "Modeling the diffusion of residential photovoltaic systems in Italy: An agent-based simulation", *Technological Forecasting and Social Change*, 106--131.

Prognos (2014), "Entwicklung der Energiemärkte: Energiereferenzprognose", Prognos AG (2014).

Safarzynska and Van den Bergh (2010), "Evolutionary models in economics: a survey of methods and building blocks", *Journal of Evolutionary Economics* (2010), 329--373.

Steinbach and Staniaszek (2015), "Discount Rates in Energy Systems Analysis", Buildings Performance Institute Europe (BPIE) and Fraunhofer Institute (2015).

Wüstenhagen, R., Menichetti, E. (2012) “Strategic choices for renewable energy investment - Conceptual framework and opportunities for further research”, Energy Policy, Volume 40, 1-10

Appendix A

	Gas Prices	
Year	price (p/th)	Price (£/GWh)
	Reference	Reference
2012	59.64	20,349.5
2013	67.88	23,159.0
2014	49.93	17,036.0
2015	42.58	14,526.6
2016	29.00	9,894.3
2017	32.00	10,917.8
2018	32.00	10,917.8
2019	32.00	10,917.8
2020	32.00	10,917.8
2021	35.00	11,941.4
2022	38.00	12,964.9
2023	41.00	13,988.5
2024	44.00	15,012.0
2025	47.00	16,035.6
2026	50.00	17,059.1
2027	53.00	18,082.7
2028	56.00	19,106.2
2029	59.00	20,129.8
2030	62.00	21,153.3
2031	62.00	21,153.3
2032	62.00	21,153.3
2033	62.00	21,153.3
2034	62.00	21,153.3
2035	62.00	21,153.3
2036	62.00	21,153.3
2037	62.00	21,153.3
2038	62.00	21,153.3
2039	62.00	21,153.3
2040	62.00	21,153.3
2041	62.00	21,153.3
2042	62.00	21,153.3
2043	62.00	21,153.3
2044	62.00	21,153.3
2045	62.00	21,153.3
2046	62.00	21,153.3
2047	62.00	21,153.3
2048	62.00	21,153.3
2049	62.00	21,153.3
2050	62.00	21,153.3

Table A: Historical and projected gas prices in UK model (source: "Reference" scenario in BEIS (2016a)

Appendix B

	EUR/TJ	EUR/MWh
2012	8,067	29.0
2013	7,656	27.6
2014	6,538	23.5
2015	5,618	20.2
2016	4,275	15.4

Table B1: Historical gas prices in German model (source: BmWi Energiedaten database)

	EUR/TJ
2020	30
2025	31
2030	31
2040	33
2050	33

Table B2: Projected gas prices in German model (source: Prognos,2014)

	EUR/t SKE	EUR/MWh
2012	93.02	37.0
2013	79.9	31.8
2014	73.55	29.3
2015	72.74	29.0
2016	67.07	26.7

Table B3: Historical hard coal prices in German model (source: BmWi Energiedaten database)

	USD/t	EUR/t	EUR/MWh
2012	111	79.9	31.8
2013	115	82.7	32.9
2014	117	84.2	33.5
2015	122	87.8	34.9
2016	123	88.5	35.2

Table B4: Projected hard coal prices in German model