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Modelling sustainable energy futures for the UK

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ABSTRACT

As a result of signing the Kyoto Agreement the UK will need to reduce carbon emissions to 20% of their 1990 value by 2050. This will require a complete change in power generation over the next 40 years. The system involved is immensely complex, with multiple agents, levels of description, new technologies and new policies and actions. However, here we develop a relatively simple spatial, dynamic model representing a basic part of the problem – the changing geographical distribution of electrical generation capacity in the UK. It runs from 2010 until 2050 and allows the exploration of the different pattern of investments in, and closures of, generation capacity. It was develop as part of the CASCADE project on Smart Grids to provide scenarios for annual changes in generating capacity. It provides generation scenarios for much more complex, multi-agent models, such as that developed in the CASCADE project, that represent the short-term (30 min time step) dynamics of the wholesale and retail energy markets. The model allows us to explore different possible pathways to 2050 and the difficulty of the overall endeavour. In order to increase electricity production but reduce CO_2 emissions, we shall need to close our current coal/gas generating plants and make a vast investment in new low carbon generating capacity. The model allows us to rapidly the possible consequences of innovations in technologies, and to re-shape plans in the light of as new opportunities and circumstances.

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1. Introduction

In a recent paper Sardar [1] put forward the idea that we are living in ‘post normal’ times. This was further extended by Gary, [2] who suggested it pointed to a new understanding of macro-history of social-ecological systems according to the views of Holling [3] where systems’ evolution proceeds through successive periods of development, break-up and re-development. And ‘complexity thinking’ more generally has also arrived at a somewhat similar overall view of the evolution of ecological, social and economic systems [4]. Complex evolving systems have periods of qualitative structural stability, when development and specializations grow as part of the co-evolutionary adaptations within a stable organizational structure. But, such periods are separated by interludes of instability, breakdown and collapse of old structure as new features, technologies, variables and characteristics emerge [5–7] and lead to a new period of qualitative stability. This overall view recalls the ‘Long Waves’ of Krondatieff and also Schumpeter’s [8] view of waves of ‘creative destruction’. So the idea of post-normal times and of macro-history being something in which previously stable structures and systems become

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unstable and lose their coherence, before perhaps re-developing into new organizations and forms, agree very much with the behaviour of complex, evolutionary systems.

Today, our own ecological, social and economic systems are pushing us towards a potentially catastrophic climatic instability that we need to avoid. Energy is one of the most fundamental factors of all systems. But now after several hundred years of industrial and technological growth based on the unrestrained use of fossil fuels to multiply our own capacities for work many hundreds of times, this 'economic growth' system has reached a crisis. Our models of climate change, now very sophisticated, suggest that continuing on a 'business as usual' path would quite possibly tip the planet into a major reconfiguration of its climatic, ecological and socio-economic structure with catastrophic effects on the human population. So in many ways we are now precisely trying not to tip the global system into a re-structuring event which might leave little place for us in it. We are trying to stop macro-history from delivering us a knock-out blow.

But "modulating changes towards sustainability is not an easy task: consequences of environmental problems will occur only in the future while the complexity of socio-economic interactions makes it difficult to foresee effects of policy measures over time" [9]. Recently, Transition Studies [10–13] have emerged in order to address these problems of attaining sustainability. These ideas have been applied to several separate industries [14–17] as well as attempts at an integrated view as an aim for a sustainable society [18]. These ideas also take a Multi-Level Perspective [19] on systems as there are clearly interlinked dynamic levels which they refer to as niche, regime and landscape. Historical cases are analyzed with an MLP while unfolding case studies transition management.

In fact, complexity studies had already demonstrated that at least three levels of description co-evolved over time: individual elements, connected elements, the environment [5]. In these models the individuals (micro) can change their behaviour either spontaneously, by imitation or by learning. The local system (meso) of which they are part can change because of these individual changes, or because the system links and mechanisms are changed. Thirdly the environment and system (macro) can change either because the system changes its effects on the environment or because changes in the environment affect the system and individuals. These changes might for example be technological, societal, or political. Developing different types and levels of model of complex systems can be seen as applying successively a sequence of assumption, each more constraining than the previous one.

Assumption 1. Identify system and environment.

Assumption 2. Identify variables over time (Evolutionary tree).

Assumption 3. Structural stability (no new variables).

Assumption 4. Only most probable events occur.

In Fig. 1 we see that if we can only make assumptions of a system boundary and the capacity to classify the types of elements interacting, then one arrives at a multi-level, co-evolutionary model where successive periods of structural stability are separated by instabilities during which new things emerge (an evolutionary tree) and some old ones disappear. If a further assumption is made that the system is structurally stable (no new variables or behaviours hence no learning) then we derive probabilistic non-linear dynamics. But this is still very difficult to think about and manipulate mathematically and so for simplicity, instead of dealing with all possible interactions, we only consider the most probable, average ones. We arrive at deterministic (predictive) dynamics. Of course, the problem is that these simplifying assumptions may not actually hold. But this will only become clear when our expectations based on our simplified model are confounded by experience.

In Fig. 1 we see that the full evolutionary complexity leads to at least a 3-level co-evolution as novel individual types experience differential success. There is emergence of new types, variables and mechanisms, which change the 'system'

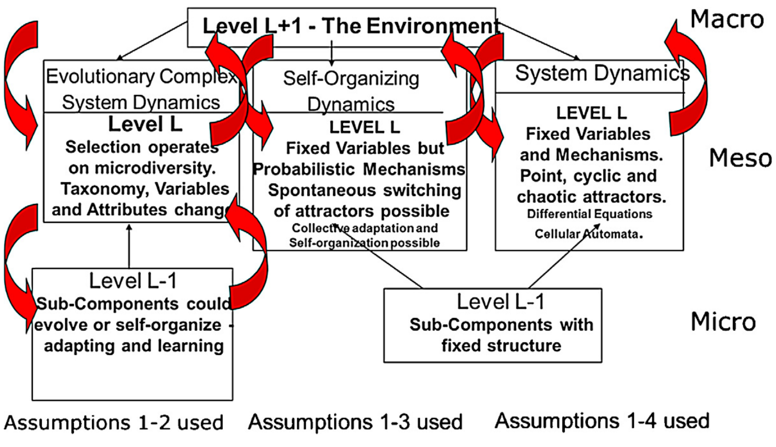

Fig. 1. Successive assumptions are made to reveal the behaviour of complex, evolving systems. These provide a multi-level perspective.

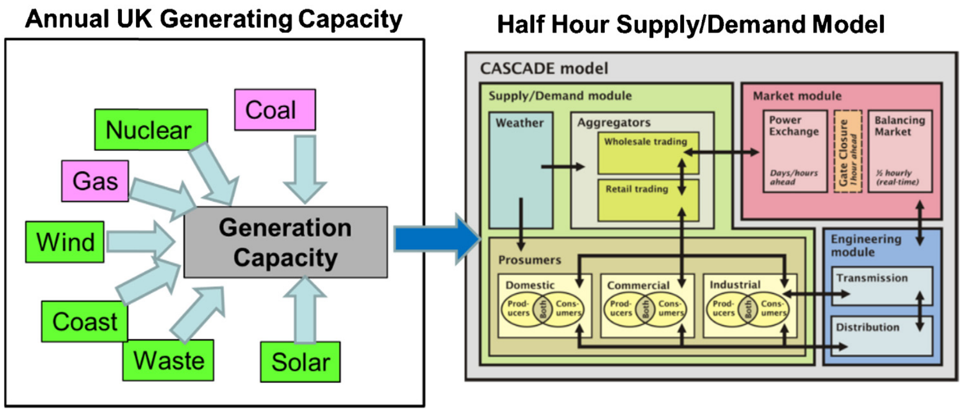

Fig. 2. The UK model of generating scenario provides an annual Scenario for the for the main CASCADE rapid time scale Model.

qualitatively and may affect the environment or context by its new capabilities and performances. However, once the Assumption 3 of structural stability has been made we only have two levels of description, because individuals cannot learn and we therefore lose the lowest level of change. The system level model can then only 'run', but in the probabilistic case includes the presence of all possible events and interactions (according to their probability), giving rise to 'fluctuations' that can 'tip' the system from one attractor basin to another spontaneously. This can lead to new regimes that allow the system to better fit the context. However, for the deterministic system dynamics the model can only 'run'. This latter type of model is popular with decision makers because they appear be getting hard predictions from the system trajectories, allowing a clear view of the consequences of any action or policies. But, in reality this is a mistaken view in that it can never be known for certain that the assumptions (for example of structural stability) will hold over time. However, since we must make decisions about the future then it may be better to make and use a simple model, knowing its limitations (our assumptions) instead of trying to build a very complex representation with a maximum of details, many of which cannot be known in advance. This paper is an illustration of this idea. It presents a systems model that can be run to illuminate different possible futures based on some rather stable long term mechanisms that are present. The model presented here is therefore only a simple system dynamics model using all four assumptions and not complex in itself. Instead of modelling the evolutionary processes within it we can explore the broad effects of technological and price scenarios over the long term so that policy options can be rapidly reassessed if necessary (Figs. 2 and 3).

A key difference between our current situation and a 'normal' one where planning is about improving future performance in a given situation, is that we think that continuing with 'business as usual' could change our situation and its context towards a climate catastrophe. Instead of simply planning how to play 'the game' a bit better, we are trying to avoid destroying the game and the context itself. One other difference between 'transition thinking' and 'complexity thinking' is that the former seems to take a view in which equilibrium exists 'before' transition and again 'afterwards', while complexity thinking suggests the idea an un-ending process of change and learning, necessarily incomplete and leading to further change and learning. Despite all this, however, for some periods the structure and organization of the system can perhaps be viewed as qualitatively stable while at others new variables, features and capabilities can emerge.

Of course, planning and decision making have usually been based on an understanding of the situation and of the way to improve the outcome. But this was all within a continuing context and a particular ecological, social and physical environment. Today the threat is of a wholly different order. We are trying to stop, or not to cause, a massive global instability. We are trying to dramatically reduce our CO_2 emissions and generate the energy we still want through the use of renewables and non-fossil fuels. It seems a rather banal focus for such an important coming-of-age for humanity. It concerns the practicalities of building wind farms, nuclear power stations and tidal barrages.

In order to reduce CO_2 emissions by 80% in 2050, the plan is to move from the variety of heating technologies for homes and business to electrically powered heat pumps and to 'electrify' transport with the changeover from petrol and diesel to battery powered vehicles. When we add into these requirements the fact that it seems probable that the UK population will rise from 64 to 74 million by 2050 then probably we shall need to triple electricity production while simultaneously reducing CO_2 emissions by 80%. This is a very difficult transformation to achieve, particularly when we reflect on the fact that much our society is driven by self-interest and the quest for short term profits. It will be remarkable if we can devise policies of subsidy and taxation that succeed in taking us to sustainable, renewable energy by 2050.

Energy targets in the UK are still making headline news as the industry regulator predicted a huge fall in reserve capacity [20] and the building of new nuclear capacity is still extremely unpredictable. Against this background the search for the necessary parameters to frame a model of electricity generation is challenging. However, some anchorage can be found in the government's legally binding 2020 target and the five yearly carbon budgets set at least 15 years ahead, which are also legally binding. According to the Committee on Climate Change (2012) this or indeed any path ahead requires almost complete decarbonisation of electricity generation by around 2030. Less certain – but consistent with current policies both in the UK and internationally – is that electricity will become even more significant than its current share of emissions implies, as moves towards the electrification of heat and transport accelerate.

The UK is legally obliged to reduce its energy emissions by 80% of the 1990 value by 2050. There have been extensive modelling and planning in order to achieve this. The three major initiatives are:

- The Pathways programme on the DECC website is certainly a remarkable innovation in Government communication over such matters [21]. This model allows people to explore a variety of possible futures and the government has itself used it to set out four possible Scenarios that it considers illuminating to both consumers and suppliers. Their view is that electricity consumption might double by 2050 – and of course that this will have to be produced by low carbon generation such as nuclear, wind, solar, wave, tidal, etc.
- The report from the National Grid [22] comes out with a suggested growth in electricity demand by some 50% of current levels by 2050. Again this would need to be generated by low carbon technologies.
- The UKERC has also explored the changes in the energy system that would be required if we are to reduce CO_2 emissions by 80% of their 1990 values. To do this they have used a large economic model, MARKAL, and explored the assumptions necessary to generate enough energy and electricity over the period 2010–2050.

These reports and models are very useful in setting out the size and scale of the problems that we face, and in laying out pathways that could be taken. The MARKAL family of models are least cost optimization models based on life-cycle costs of competing technology pathways (to meet energy demand services). They are partial equilibrium models assuming rational decision making, perfect information, competitive markets, perfect foresight and optimal actions each year. They are not spatial models. However they are very detailed and thorough and have provided an important basis for reflection and policy making for the UK. Without dismissing in any way the importance all this work, the paper presented here puts forward a relatively simple, dynamic spatial model of the interaction between supply and demand for electricity from 2010 to 2050. None of the other models above are spatial. Our model can help the user explore dynamic pathways into the future with the aim of arriving at 2050 with an 80% reduction in carbon emissions – but hopefully with the same comfort levels as at present. It can explore the spatial distribution of the different low carbon generating capacity. It demonstrates the scale of the difficulties we shall face in this achieving this and allows the modeller to explore different levels of concern for environmental as opposed to economic considerations. It was developed as part of the CASCADE project and tries to illuminate the consequences of choices that we make concerning electricity generation.

2. A simple spatial model of the UK electricity system 2010–2050

The model of the UK energy system allows the exploration of possible futures under varied assumptions concerning the costs and impacts of different generation technologies. The model is distributed spatially over the UK and shows how different pathways can take the UK to an 80% reduction in CO_2 emissions in 2050, with a tripling of generation to 180 GWs. This large increase in production results from assuming that both transport and heating will be electrified and that electricity generation will be done largely by renewables [23]. Also the current levels of population growth are used and suggest a 2050 population of over 70–75 million.

The model presented here was developed as an auxiliary part of the CASCADE project [24], designed to create scenarios for the annual input parameters for more detailed models of daily trading within the electricity wholesale and retail sectors. It was aimed at exploring the effects of different assumptions about emissions, costs, technologies and environmental impacts other than CO_2. The main part of the CASCADE project was about modelling the use of Smart Grids in the short term patterns of supply and demand for electricity.

The model here is based on an earlier 'self-organizing' logistics model in which the structure of distribution systems emerged from a dynamic, spatial model. In this model the choices made by consumers, together with the non-linearities of costs for warehouses handling different volumes of goods, led to the spontaneous emergence of a distribution hierarchy. The emergent structure of centres provided an efficient distribution of goods through national, regional and local distribution centres. The model had the advantage of being able to adjust its structure if costs or customer demand changed.

Now the UK electricity supply system does not correspond at all to this idea of consumers choosing their point of supply. Instead we have a top–down system in which power is generated in large power stations and put onto a grid that distributes it relatively logically to consumers. But, consumers do not choose the exact source of their actual 'electricity', since in any case supplies are all aggregated on the National Grid. People choose only the organization and tariff scheme they sign up to. These can be 'aggregators' who may or may not actually have power stations themselves, but may simply be 'traders', making contracts with generators and with consumers. Despite the apparent difference of this with the simple problem of goods distribution described above, we will see that these 'bottom-up' ideas are relevant to the planning of an effective pattern of supply.

In broad terms we must recognize that today most domestic heating and hot water is supplied by gas, and electricity is used mainly for lighting, cooking, entertainment and communications. Similarly, transport is overwhelmingly powered by petrol and diesel engines. We can rapidly see that the 'low carbon plan' to switch heating and hot water and a large part of transport over to renewably generated electricity together with its present uses, for a probable population of over 70 million, represents a massive increase in demand. This means that, unless we accept a radical change in lifestyle (e.g. almost no travel, or heating!), or insulate our houses and offices to a very high level, over the next 40 years electricity supply must approximately triple! and at the same time we must decrease our carbon emissions by 80% of their 1990 value. This means that in large part we will have to add new, low carbon generating capacity across the country. The problem we are examining here therefore is that of 'when to put what, where' in the intervening years between now and 2050.

The question our model can explore is how different types of agent might view the attractiveness of different energy supply investments and provide an instrument to explore the consequences of a particular choice. In this way such a model could be the focus of discussion among the numerous stakeholders as to the relative attraction of the different possibilities at different locations. Our choice model will therefore include a multi-dimensional value system that will reflect financial costs, CO_2 reduction and other possible considerations.

The basic structure of the model is that each year we calculate:

What is the current pattern of demand and of 'stress'?
What is the current pattern of production of type E?
What changes in the distributions of each E do we want to make this year if we are to arrive at 2050 with the correct capacity and CO_2 emissions?
Calculate the pattern of investment and of closure.
Calculate the new levels of supply and demand for the different technologies E.

Calculate next year.

The model first calculates how much of a given technology it would like in 2050 and it compares this with how much it has currently. Thus it calculates how much of each type of power generation it would like to add or close each year. It then takes each of these amounts and looks at the relative attractivities of the different geographical locations for either placing new capacity or closing old. At the level of households and businesses, the micro-level, the growth of solar, wind and CHP schemes would continue reducing to some extent the demand present.

The most basic components of the attractivity of a particular technology E is given by:

$$\text{Attractivity(E)} = e^{\{-\text{Va1}.\text{CO}_2(\text{E}) - \text{Va2}.\text{LCE(E)}\}} \tag{1}$$

CO_2(E) is the table of values for the carbon emissions per kWh from the different energy sources and LCE(E) is the table of costs per kWh for different types of generation [26]. Va1 and Va2 reflect the relative importance of carbon reduction and to financial cost that the model is testing. It can test the effects of different preferences of a model user. The model first calculates the attraction of a given investment of type Energy (E),(Coal, Gas, Nuclear, wind, etc.) at point *i* at time *t* and uses this to calculate the increase or decrease required for a given technology E.

Change in capacity of type E = *r** {(ftdem × Attractivity (E)/Total attractivity) − Actual capacity (E)}*r* is a response rate and ftdem is the expected demand in 2050. This clearly calculates the relative attractivity of a given technology and uses this to guide the addition of new capacity. The model is explained in more detail in Appendix 1.

This required total change is then 'distributed' across the UK according to the attractivity of each zone i for a given E. This will depend firstly on the adequacy of energy supply at *i*. The 'stress' at point *i* will be given by the spatial/network balance of supply and demand at and around *i*. We can plot a map of the distribution of 'stress' over our 100 points of the UK. Also, geographically more distant capacity such as off-shore wind farms off North West Scotland would have to be transported down to the populated parts of the UK. These costs must also be included. So, in a particular year, we will have a pattern of 'stress' reflecting the fact that supply (at any particular moment counting on only 30% of the wind capacity) may be exceeded by demand.

This attractivity is higher if the location *i* has a high stress (demand/supply) and also if the location has a particular advantage for the technology in question. For example, if the source is wind power, then a windy location offers far greater returns. For nuclear power there will be a need for cooling water and a location that is not too close to large populations. If a zone has already had nuclear power on it then this will also increase the attraction. Similarly, for coastal power (tidal or wave) we need to be on the coast but also some stakeholders may view the ecological impact of a tidal barrage (such as the Severn Barrage for example) to outweigh the value of the electricity generated. For wind power the pattern of attraction is affected by the map of wind speeds for the UK, but clearly also there are local stakeholders that consider the aesthetic impact of the installation to be extremely negative. Similarly, solar investment initiatives are favoured by the amount of solar radiation that falls in a zone. Similarly, to produce clean coal or gas will require suitable holes in the ground to pump the CO_2 and so locations that have already had coal mining or oil/gas extraction will probably be more suitable that locations that have not [27]. We can also allow for the 'saturation' of a zone as a function of capacity that is already installed. So, there is a limit to how many wind farms one can put in a zone, and waste and biomass incineration require populations or land to provide the raw materials. Each location also has its own 'predispositions' that affect its attractivity.

We must also allow for the time delay in between the decision to start building a facility and the time it takes for it to come 'on-line'. So, for example, we may initiate the building of a 3 Gw nuclear power station at a particular location, but it will only start producing power (very optimistically) after 8 years. These delays underline the importance of this kind of policy exploration tool, because it makes clear how early decisions have to be taken in order to avoid periods of supply failure.

The environmental impacts of the energy production can be the corresponding carbon emissions (kgs of CO_2 per kWh of electricity) but could also represent radiation risks, noise, or impact on wild life. Generally speaking however, the most common factor taken into account by actual decision makers will be financial costs. LEC, the levelised energy cost is the total cost incurred in generating electricity from a particular source for its lifetime of perhaps 40 years. It includes initial investment, operations and maintenance, cost of fuel, cost of capital, and therefore allows us to see the relative costs (e.g. £/kWh) of different possible choices. It helps us see which energy type would reduce the stress for the least total cost.

Our model will consider the balance between the monetary costs of power generation (£/kWh) and the CO_2 emissions (CO_2/kWh) and environmental costs involved. This would allow us to consider the impact of different rates of carbon tax. If carbon taxes are high then low CO_2 technology will be more attractive. In this way we can calculate the relative attractivity of different possible types of investment at a given location and at time t. The stress (i, t) takes into account the vulnerability of a given zone reflecting the degree to which demand is a high proportion of possible supply. The relative importance of the costs and the reduction in CO_2 would reflect the values of the decision maker, as would the discount rates applied. The model could reflect the difference between a 'National Decider' as opposed to regional or local deciders, who would clearly weight their own situations more strongly.

Our model can include the effects of different kinds of support for the development of low carbon technologies and subsidy for its growth. For example, for wind farms in Denmark, UK and Germany it has been possible to calculate the impacts of research support on initial innovation and also as capacity and experience grew the added effects of 'learning by doing' [28]. This type of effect can be included in our model. Including R&D endogenously in our model could give rise to multiple possible path dependent trajectories. This recognizes some of the issues raised by the theoretical study of [29], 2009, when they used partial equilibrium methods to study the effects of endogenous R&D and increasing returns in the take up of a technological breakthrough in renewable energy. Similarly, the model could also be used to consider the use of integrated socio-ecological and economic measures to assess in a broader way the advantages and disadvantages of particular pathways and choices [30]. In our framework there is a clear place (the attractivities) where we can insert a series of factors that go beyond simply cost and CO_2. It could include a wide range of impacts and allow an integrated assessment process to guide the decisions.

Generation near to large populations will tend to be on more expensive land, while the distant wind farms in the North Atlantic will have long transmission lines and high maintenance costs but will provide low carbon energy. The model can now be run under a series of possible scenarios concerning the costs/effectiveness of technologies such as Clean Coal/Gas, the sentiment for or against nuclear. With these assumptions we can explore the outcomes of the model as we attempt to reach the 80% reduction in emissions while tripling the power generated.

3. Initial model results

In this preliminary version of the model, the geographical space for the simulations will be 100 points representing the UK. The model will take the take the current distribution of generating capacity and then look at the annual changes brought about by:

- end of service closures
- closures for carbon reduction
- new capacity either coal, gas, nuclear, wind (on or Off shore), marine, biomass and solar.
- The continual growth of household and neighbourhood level schemes for solar, wind and CHP.

Each year the model allocates capacity according to the technology and the zone. The 'model' then makes these changes and recalculates the pattern of supply and the growing demand – which is increasing both because of the growing population and also the electrification of transport and of heating. The model also calculates the CO_2 emissions and if the supply is deviating too much from the trajectory towards an 80% reduction by 2050, then the attraction of low carbon generation increases compared to higher emission technologies. In this way the model attempts to achieve the policy aims for 2050. As the Grid brings power from other points of production it incurs transmission losses and so clearly the more distant the supply is from demand the greater these will be. Our model can therefore help to create a more 'compact' pattern of generation by allowing for the costs of transmission and hence making choices that reduce these losses thereby decreasing the overall costs of power.

Overall the model explores the effects on the ground of our decision to reduce emissions to 20% of their 1990 levels. The energy currently coming from oil and gas that is used in transport and heating will be changed to electricity, generated using low emission technology. However, the implications of this are that electricity generation will need to increase from the current 55 GWs to possibly 180 GWs by 2050, and at the same time emissions will have to fall from the current 27,000 tonnes to around 6000 tonnes. This is an extremely demanding outcome. It means that we must add a great deal of low carbon generation capacity (Wind, Hydro, Nuclear) and can afford a diminishing amount of even 'Clean' coal or gas. This simulation runs at a 'long time scale' 2010–2050. Each year the model finds the most attractive locations for new or increased low

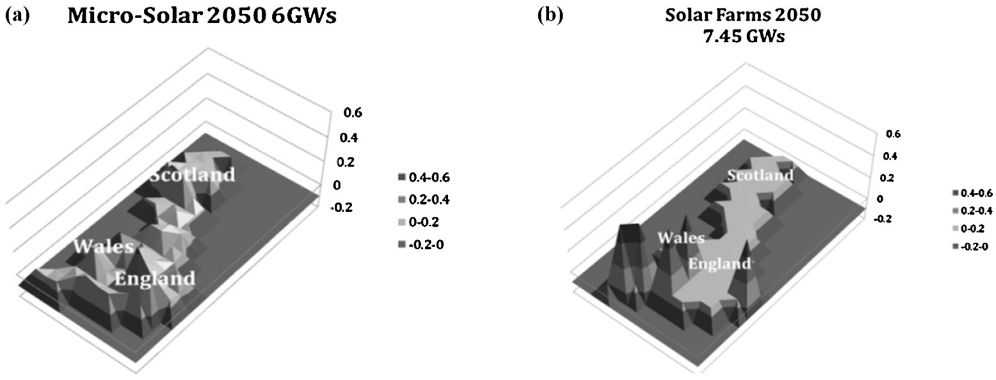

Fig. 4. (a) The distribution of micro-solar power. (b) Distribution of solar farms by 2050.

carbon generating capacity or for closure of old coal and gas generation. The results below show one particular outcome purely as an illustration of what the model may show when properly calibrated.

The western side of the UK and the less populated zones are more attractive as locations for macro-wind capacity, while the micro-solar is installed by local populations, and the return is geographically higher in the South-East. The simulations are shown below starting from an initial situation with low installed capacities and changing over time to provide significant quantities of electricity. Va1 and Va2 are the relative weight we attach to carbon reduction and to financial cost. The contribution of solar PV is rather expensive and without exceptional subsidy would be relatively small.

Micro solar reflects the population and roof areas while 'solar farms' reflect the general levels of irradiation as shown in Fig. 4b. However, both of these only make a relatively small contribution to energy generation (Fig. 5).

The next two figures show the distribution of nuclear power stations from 12 GWs in 2010–2050 where in this run we have 36 GWs.

In this simulation both clean coal and clean gas play a relatively small role, but this depends on the costs and CO_2 emissions that will characterize this currently unproven technology. This may be because the available, leak proof geological storage capacity is not large or that the costs of cleaning flu gases and sequestrating the CO_2 are really very high. Obviously, the effects of changing these assumptions can be tested using the model.

The largest contribution to generation however comes from wind farms both on and off-shore.

The model shows in Fig. 6 that off-shore rises steadily to 46 GWs and on-shore spreads widely across the landscape rising to 34 GWs by 2050. But with nearly 50% of generation as wind the problem of intermittency does mean that we may need some 30 Gws of standby to take care of prolonged windless period across the country. But in fact this has a very low probability and with a large geographical spread (up to 100 kms) the probability of zero production is very small.

We also have to allow for Coastal power generation through tidal barrages and wave generators, as well as for biomass generation based on wood, miscanthus or ethanol production. The 2050 distributions of coastal and biomass power generation is shown in Fig. 7a and b.The overall growth and decline of the different possible power sources is shown in Fig. 8.

For a typical model exploration, demand, following the electrification of transport and heating, the demand is for 180 Gw. In order to respond to peak demand, the total capacity is 196 Gw and the growth of the different types of power generation is shown in Fig. 8a. CO_2 reduction is indeed around 80% as required. In Fig. 9 we see the distribution of Stress which reflects the ratio of demand over supply (firm production plus 30% of the intermittent capacity).

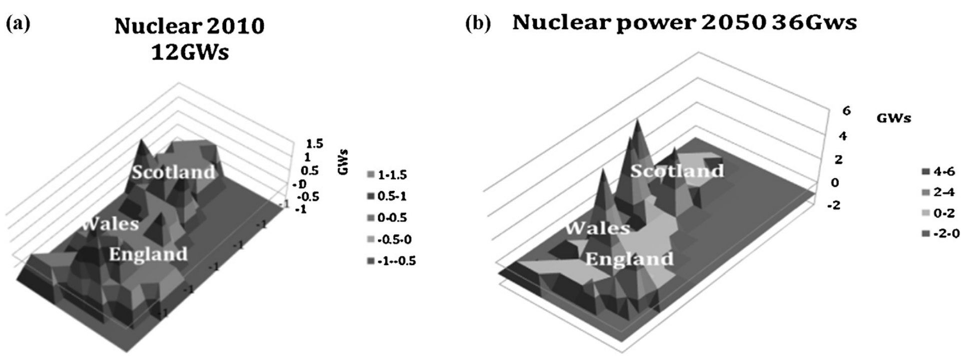

Fig. 5. (a) Nuclear production in the UK in 2010. (b) Nuclear production rises to 36GWS in 2050.

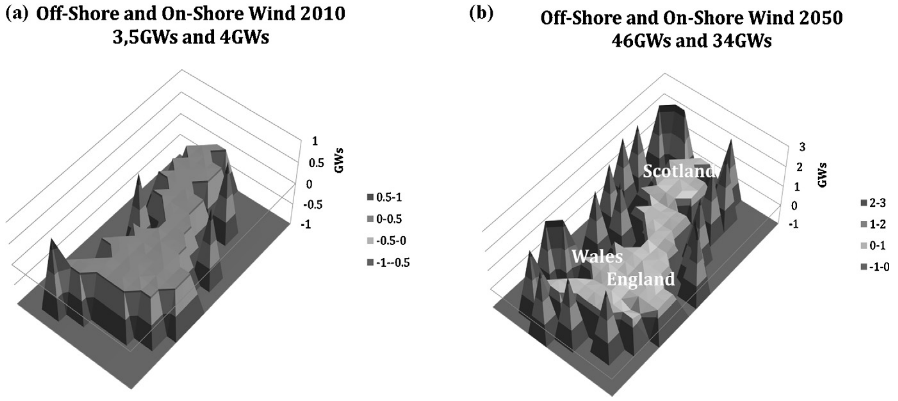

Fig. 6. (a) Wind generation at 7.5 GWs in 2010. (b) By 2050 wind power rises to 80 Gws.

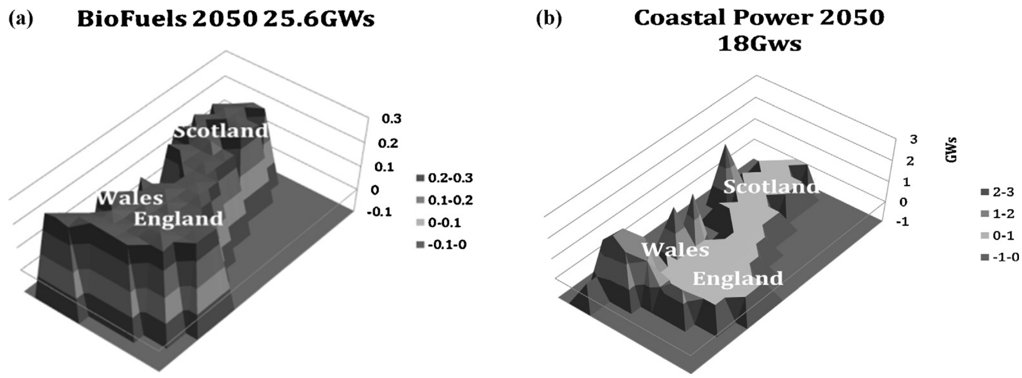

Fig. 7. (a) The distribution of Bio/Waste generation in 2050. (b) Distribution of Coastal (tidal and wave) power in 2050.

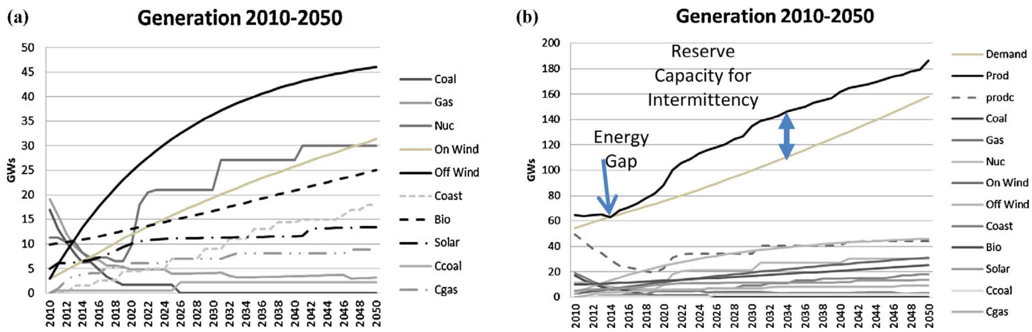

Fig. 8. (a) Different types of Generation 2010–2050. (b) Showing growing demand and production of electricity 2010–2050.

The outcomes suggested by the model can help our policy reflections by allowing us to view various 'possible futures'. This illustrates the utility of the model for exploring different possible pathways to 2050. The six different scenarios are:

- 113 Va1 = 1, Va2 = 1, Off-shore wind on. (Equal weights for CO_2 and cost)
- 013 Va1 = 0, Va2 = 1, Off-shore wind on. (Only financial cost counted)
- .113 Va1 = .1, Va2 = 1, Off-shore wind on. (Very weak CO_2, heavily weighted for financial cost).
- Low N 113, Va1 = 1, Va2 = 1, Off-shore wind on Nuclear held low. (Equal weights for CO_2 and costs)
- Low wind 110, Va1 = 1, Va2 = 1, On and Off-shore wind held low. (Equal weights for CO_2 and costs)
- HighCTax, Va1 = 1, Va2 = 1, Off shore wind on and high tax on CO_2. (Equal weights for CO_2 and costs but with high carbon taxes)

The low wind and low nuclear scenarios require great investments in coastal generation and bio/waste production to still attain the 80% CO_2 reduction and sufficient power 190 GWs. This is telling us that although we may not like nuclear or wind generation, we would have a very difficult time to generate enough low CO_2 power without them!

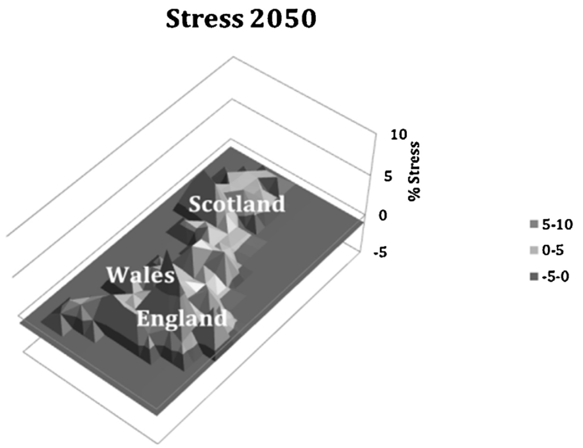

Fig. 9. The spatial pattern of stress in 2050, where stress is demand over supply, where supply is firm supply plus 30% of the intermittent production.

The model allows a rapid exploration of the possible changes that new technological breakthroughs may allow. As new storage technologies, clean production techniques, etc. are discovered the model can be used to assess their importance and make new plans. Clearly, if we have a great deal of wind generation then we have to allow for its potential intermittency and this is already taken care of in the Fig. 10 above. We have allowed for extra standby capacity to fill in for intermittency of wind power. But we can imagine different ways of 'smoothing' it for example by pumping water up Norwegian mountains or by having local batteries in each neighbourhood. Each of these is technologically possible and so there will be many further advances that can help us reduce the peaks and troughs of demand, and the intermittencies of wind, wave, solar and tidal generation. Clearly, we can start to put figures on the 'savings' that the SMART GRID could bring about in allowing us to handle peak loads without building all the capacity required.

4. Conclusions

The simple dynamic model presented here looking at possible pathways to sustainable energy production for the UK can help us reflect on different possible futures. And we should not believe that a model such as this will accurately predict what will happen in reality, because it is fairly simple, and also many factors and elements within it will change over time in ways that we cannot guarantee to anticipate. The world viewed through 'complexity' spectacles is unendingly creative and surprising. Some surprises are serendipitous, others are unpleasant. We need to explore possible futures permanently in order to see when problems may occur or when something unexpected is happening, as we use our models and our experience to develop judgement as we 'experiment' and 'reflect' on the situation of interest.

In dealing with the world we develop 'interpretive frameworks' which represent our current beliefs about the entities involved in a situation and the connections that exist between them. In Fig. 11 we show a simple picture of this.

But our interpretive framework only reflects our current understanding of a situation. Over any significant period at least some of the agents involved will change their views and opinions and behaviour. The reason is that peoples' interpretive frameworks change and so do their resulting opinions and actions though not necessarily in a logical or rational way. Over time, our interpretive frameworks are tested by our observations and experiences. If our expectations concerning what will probably happen are confirmed then we tend to reinforce our beliefs. When our expectations are denied however, we must

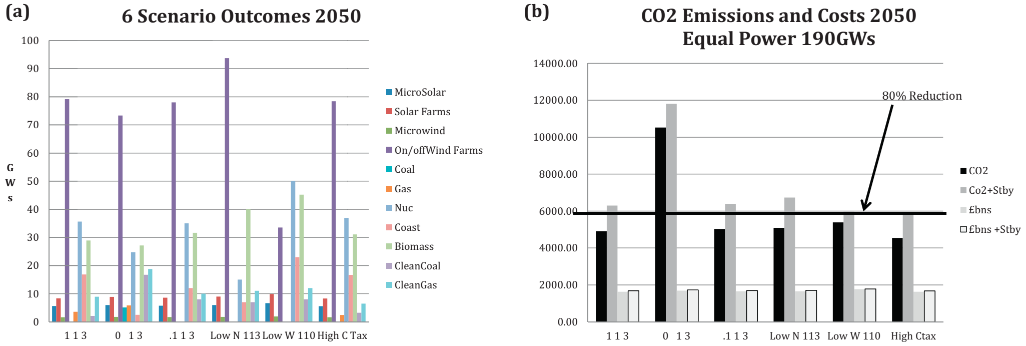

Fig. 10. (a) The detailed outcomes of 6 scenarios. (b) Five of the outcomes lead to an 80% reduction in CO_2.

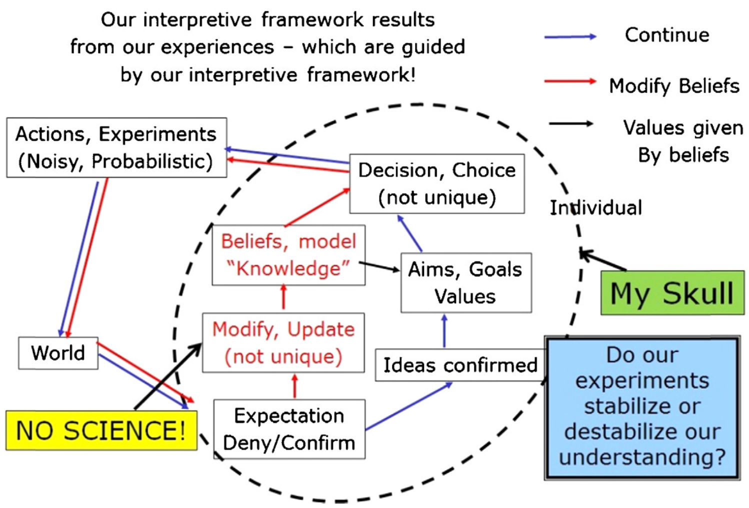

Fig. 11. Experiences confirm or deny the expectations we have that are based on our interpretive framework. Confirmation leads to reinforcement but denial leads to uncertainty. Learning is not a science.

face the fact that our current set of beliefs is inadequate, or as in often the case respond by declaring the evidence false and sticking to previous views. But even if we are 'honest seekers of truth' there is no scientific method to tell us how to modify our views. Why is it not working? Are there new types or behaviours present? Or are their interconnections incorrect?

In reality, we simply have to experiment with modified views and try to see whether the new system seems to work 'better' than the old. Our interpretive framework is really just a tool within the pragmatic approach that complexity forces us to adopt. Fig. 11 is just a classic learning diagram. But, in the real world, the multiple agents involved in any situation will vary in their degrees of willingness to change their beliefs and in any case will change them in different ways, since there is no scientific method for how this should be done. This is why models of situations involving multiple agents that claim to predict the future will fail, and points to the virtue of having simple models that can provide some rapid assessments of the effects of new information and circumstances. If we had to develop a really complex, detailed model of everything and show that it was really valid, then we would only be able to model the past – and for decisions and actions this might be too late.

Of course our current beliefs will include which of our beliefs are most likely mistaken, whose ideas or comments we should trust and listen to and those we should discard. And some people may be happy to take on new ideas every day, while others may choose never to modify their beliefs, feeling that the increasing evidence of inadequacy is merely a test of their faith. So the diversity of different agents will lead to a messy 'cognitive evolution' that allows new beliefs to generate different behaviours, and to view their degree of success. This allows beliefs, interpretive frameworks and models to evolve over time, and to change the world in consequence. It points to the idea that we should always be looking at our own actions as "experiments" that test our understanding of the way things work.

Clearly, given the lack of any clear scientific method on how to change one's own beliefs, many may simply adopt the views of their preferred group, and simply mimic their responses, without necessarily understanding the basis of these. This may explain the importance of 'social networks', and the 'wisdom' or 'idiocy' of crowds.

Evolutionary complex systems and models are creative and surprising, but this does not tell us that 'simple models' are useless. If simple models suggest a way forward, then we may have to act in partial uncertainty but with an eye to using our model to monitor how the system may be deviating from its expected behaviour, and how new technologies and costs have altered the calculations. The simple model of the UK electrical generating system presented here may point out key problems and issues which can then be examined in more detail by a more sophisticated and detailed model. Another potential use might be that of continuing spatial devolvement of powers, so that the model could explore the UK patterns of generation if local politics made the choices.

In the approach used in CASCADE we have looked at the complex overall problem in terms of two different time-scales. Firstly the fast, very complicated multi-agent dynamics of the wholesale and retail energy markets that links the current generating capacity to the current demand in 30 min steps. And secondly the longer time-scale (annual) spatial dynamics of the changing pattern of generating capacity that must be fed into the fast model. The characteristics of the long term generation capacity affects the short term model by its level of intermittency and overall power availability. This long term model is what we have presented here. Although low carbon generation is required in the long term, the difficulty of achieving this can be greatly alleviated by the use of Smart Grids and local storage within the fast dynamics of the wholesale and retail markets. These can greatly reduce peak load requirements and deal with intermittencies of renewables and so the short term feeds back to the long term by changing generation capacity requirements.

Complexity calls upon us to recognize the limits to our understanding of humans and their technological support systems, such as the built environment, cities, transport and trade networks, ecosystems and the environment. Our knowledge is always partial, limited and temporary. For this reason it is sensible to break systems into different levels of description and time scales, and to make models that can be understood more easily, but which are connected together in reality as an evolutionary complex system. Instead of trying to understand the whole multi-level system in a single highly complex model, it may be helpful to break it into models of different spatial and temporal scales, but still realize that over time their connections will lead each of them to co-evolve. In reality there are multiple mechanisms, issues, understandings, values, goals and behaviours that co-habit the system at any moment, and these change over time as the system and interpretive frameworks co-evolve. We are part of this creative, complex evolution and so we will have to continue our imperfect learning process using successive frameworks and models as we go. There will be no end to history, no equilibrium and no simple recipes for prediction and success. The question of changing our systems radically to depend on low carbon energy systems is one of the most profound that has faced humanity. And we shall only avoid catastrophic climate change by going beyond the 'short term' business-as-usual and this is why we have to split the problem into long and short term parts, so that policies that change the long term can be explored. So far, we are still following the 'predictions' made in the Limits to Growth forty years ago! This is perhaps largely due to the political fixation of recent decades on the superiority of 'free market systems' despite the fact that there are only a few dominant players in the wholesale part of energy generation. These, not unnaturally, are focused on short term profits rather than long term planetary threats. The simple model presented here can help show the policies that will be required to tempt the actual agents, those that decide on the building of new generating capacity of appropriate kinds, to respond to our longer term needs.

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Appendix 1. The UK energy model

The first part of the model sets up the initial conditions for the simulation. It has 100 zones, the 100th of which is used for the off-shore wind variable. The different technologies considered are: Coal, Gas, Nuclear, Wind (on and off-shore), coastal (including tidal, wave, and currents), Biomass and waste, and clean coal and clean gas. The initial amounts of different technology generating capacities are then distributed on the map. The initial power and CO_2 generated. The population is distributed on the map and used to map electricity demand. The distances between zones is calculated and because this is used in calculating the distances of flows of electricity we make some approximate representation of the zones where the National Grid is absent, such as parts of the highlands of Scotland. We then plot the windiness values for the different zones as well as the solar potential. The model then considers the initial technological coefficients for the different technologies and also the degree to which this might be improved in the 40 years until 2050. The model allows us to input specific suitabilities of different zones for the different technologies. For example, Coastal power whether tidal, wave or current will require that the zone be on the coast, and in particular the locations of possible large projects are known. Nuclear sites are more easily suitable for new nuclear generation if they have previously had nuclear power stations located there already.

The model then starts to calculate, for each year the changing demand for electricity as heating and transport are switched over from fossil fuels to low carbon electricity. The growth of the population is considered but it has been assumed that we maintain the current pattern of spatial distribution, and that no major new cities will emerge. In considering the pattern of generating capacity there is also a known programme of closures of existing coal and oil burning capacity in line with EU regulations and also closure of old nuclear generators. The programme therefore adds in their closure schedule as well as the agreements for new capacity (such as nuclear) where this is known long in advance. This is where recent agreements with EDF to extend the lives of some generators can be inserted in the model and the effects examined as well as the impacts of new nuclear capacity just recently agreed.

The model works by calculating the distribution of 'stress' across the map, where stress is related to the ratio of demand over supply. The demand grows as heating and transport are switched to electricity and also as the population grows. The figures used for the simulation shown above is for a growth of 8.5% for 30 years as heating & transport are electrified, and also a population growth of about 6% per year. The model calculates the demand coming from each zone as well as those around it and then calculates the production available from each zone and others. These calculations use the average transmission losses to assign a cost/distance for this supply/demand calculation. This enables us to map the amount of 'stress' for the different zones.

At the heart of the model is the idea that we calculate the increase or decrease of generating capacity of the different types, and then spread this change across the hundred zones representing the UK.

For each of the nine technologies we have an equation expressing the change in total capacity of a given type e, is given by total investment available that year multiplied by the relative attractivity for each type of technology.

This relative attractivity, $\mathrm{Att}(e)$, depends on the weight attached by the user of the model to the environment (CO_2, pollution, ecosystem, etc.) compared to money.

$$\mathrm{Att}(e) \sim \mathrm{exponential}(-\mathrm{Alpha} * (\nu\mathrm{a1} * \mathrm{rco}(e) + \nu\mathrm{a2} * \mathrm{LCE}(e))$$

where Alpha is a constant expressing the homogeneity of the agents involved in the decisions. A low value of Alpha gives a weak focus on the 'best' choices while a high Alpha gives a sharp response $\mathrm{rco}(e)$ is the weight of carbon emissions per KWh using technology e, and LCE the 'levelised cost' per kWh using technology e. The parameters va1 and va2 are inserted by the user of the model and represent their attitude to the relative importance of the environment and CO_2 emissions (va1) compared to financial costs (va2). A third input parameter simply concerns the strength of the off-shore investments. Values used in the simulations for these parameters range over 0–3. Because of renormalizations within the model all that matters is their relative sizes.

Essentially this calculates the balance between the costs of CO_2 emissions and the financial cost of the different technologies. It therefore allows us to see how high a carbon tax might need to be in order to make decision makers only interested in financial costs choose low carbon technologies. The sum of all the Att(e) is SumA.

Each year we have an amount of investment available ftdem and currently an amount of generating capacity of type e, tot(e).

$$d_{\text{tot}}(e) \sim \text{ftdem} * \left\{\frac{\text{Sum}(e)}{\text{SumA}}\right\} - \text{tot}(e)$$

So successive investments reflect how near the system is to reflecting the relative proportions of different technologies that the modeller desires.

Now we look assign the new capacity to zones and need to take into account the stress of the zone and its suitability for a particular generating capacity:

For each zone i we will have:

$$\text{A}(i,e) = ((1 + 2 * \text{stress}(i)) * \text{Tsite}(i,e)$$

where Tsite(e, i) takes into account the suitability of the site for the technology e. For wind farms it contains the windiness factor, for nuclear generation it marks where nuclear centres have been before, for coastal power it has the potential for tidal, wave or current generation, and for solar it has the average solar intensity.

The model then uses these to allocate the new capacity of various kinds to each zone i. For technologies such as wind where new capacity be added in small amounts:

$$\begin{array}{c}\text{FOR}\, i = 1\, \text{TO}\, 99 \\ dT(e,i) = d_{\text{tot}}(e) * \text{A}(i,e)/\text{SumA}i(e) \\ \text{NEXT}\, i\end{array}$$

For technologies such as nuclear or coastal the model calculates where the most attractive new locations are and places a unit of new capacity on these. The new capacity does not come on stream straight away but only when the time to completion is achieved. For nuclear this might be for an ultra-optimist 10 years, and more normally 20–25 years. For coal power stations, closure is largely already in the calendar. But initially gas stations may increase and later, as the required reduction in CO_2 levels becomes stronger, so they will also be reduced. The model also calculates the impact of having domestic solar and wind and it takes into account the reduction of demand on the grid that results from this. The model calculates the changes in generation capacity for each technology and zone each year, adds them in and moves on to the next year.

The model also has a mechanism which examines how far the system is from a trajectory that will get it to an 80% reduction in CO_2 by 2050. If it is way of course, because for example the model user has only considered relative financial costs, then the model will automatically take over and assign a heavy weight to CO_2 emissions and try to achieve the 2050 goals. It may not be able to succeed however.

The model can be used to explore the consequences of different choices of va1 and va2 – concern for environmental and monetary costs. The can take on any appropriate values but in the presentation here we have chosen zero, one, two or three simply to indicate the effects. This can be enlightening for those who have not yet realized the scale of the problem we face. Also, the importance of changing plans (new plans have been announced in the last few days to construct nuclear power generators by EDF and Chinese support. Also the technological coefficients may well change rapidly as new discoveries and innovations come to market, and also with economics of scale and learning in production, so that the possible consequences of each advance can be explored rapidly.

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