2015 17th UKSIM-AMSS International Conference on Modelling and Simulation

DynEMo: A Dynamic Energy Model for the Exploration of Energy, Society and Environment

Mark Barrett
Energy Institute
University College London
London, UK
mark.barrett@ucl.ac.uk

Catalina Spataru
Energy Institute
University College London
London, UK
c.spataru@ucl.ac.uk

***Abstract*—This paper describes a dynamic energy model, called DynEMo, which is designed to investigate how society engenders time and climate varying energy service demands in the different sectors (domestic, commercial, industry and transport) and how renewable and other energy resources, can meet these demands over different time scales. Certain model inputs are surveyed and sample outputs of a modelled efficient, electrified, high renewable energy system with district heating and fuel synthesis are given. Over short time periods, DynEMo calculates demands and renewable supplies and the storage of heat, electricity and chemical energy, being used to examine the technical feasibility of proposed systems and contribute towards the design and control of dynamic, renewable systems.**

Keywords-control, demand, energy systems, supply, trade

I. INTRODUCTION

We have the goal of providing secure, affordable energy services whilst meeting targets for renewables, greenhouse gas emissions, air quality and other environmental impacts. Ultimately, to meet these objectives, energy systems will have to be predominantly reliant on renewable energy rather than finite fossil and nuclear energy. A whole energy system approach has to be modelled as the operation of all subsystems and components are interdependent. All forms of energy carriers should be coordinated together: electricity, heat, gas, biofuels, as well as energy conservation and efficiency improvements actions. The system explored aims to meet objectives for energy and environment proposed by countries and regions.

In the last quarter-century, a variety of accessible energy system models have been developed, such as MARKAL/TIMES [8], MESSAGE [7], PRIMES [14], EFOM [16] and POLES [5], EnergyPLAN [11]. A comprehensive list with available tools of future energy systems is provided in [15]. This review together with our review consisted in an analysis of 84 energy models. Our review show that each of these tools has very different scopes, resolution and algorithms and varies in terms of level of detail and complexity, the data required and time period covered, and range from simple mathematical algorithms to highly complex and sophisticated computer based models. These models have different strengths, weaknesses and applicability. We have classified them by different temporal and spatial dimensions, by application focus and simulation approach.

There is one big family related models: the energy supply and energy system model which has its origin in the late 1970, MARKAL (MARKet Allocation model) [9], the energy supply and energy system model with long-term energy system simulation PLANET (IER), the energy-economic model MARKAL-MACRO (Brookhaven National Laboratory) and the successor of MARKAL energy system model TIMES [6]. Times-Markal is an energy-economy-environmental model developed under the International Energy Agency's Energy Technology Systems Analysis Programme, a bottom-up optimization model. It does multi-year optimization by computing the least cost path of an energy system for the specified time frame. In addition to this family of models, there are also the following energy systems models: BALANCE (IEA, US-DOE), MIDAS (EU), MODEST (IKP Energy System Institute of Technology, Linköping, Sweden).

Despite the diversity of approaches found in the literature, there are a number of common challenges which we identifies, such as integrated all sectors, different layers (technology, economics, social, climatic), availability of data, the interaction and dynamics between different spatial scales and capturing these dynamics at different levels in the system etc. Also we observed that current integrated models are strictly constrained to one spatial scale; in reality energy depends on different variables at different scales, which needs to be taken into account whole together. However, they don't enable interaction of different system components with associated operational strategies as described in [1] and [10]. Furthermore, most of these models do not capture short time step dynamics, which is crucial to renewables integration. Therefore, an integrated whole dynamic energy system approach that combines characteristics of all sectors (services, commercial, transport, domestic), different energy resources (gas, oil, liquid, electricity, coal), different storage and controls in combination with short time step dynamics will provide a better understanding on how future energy system evolves over time and where investments are needed.

Within a whole system model, DynEMo simulates the whole energy system over time periods from minutes to months and calculates energy flows, economic costs and

978-1-4799-8713-9/15 $31.00 © 2015 IEEE
DOI 10.1109/UKSim.2015.104

carbon emission. The authors have continuously developed DynEMo model since 2010. It is based on a previous model DYPHEMO [2]. It has been applied and validated to UK and France for modelling the diversity and dynamics of people and dwellings combination and to assess energy storage [3] into an integrated system approach. This paper provides an overview of the model, its capabilities with an output example of the whole energy system approach.

II. A WHOLE ENERGY SYSTEM APPROACH

The DynEMo model has been designed to be easily updated and modified for particular analysis, having the capability to automatically output graphs. A diagram of the principal components of the energy system, its environment and its control system is provided in Fig. 1.

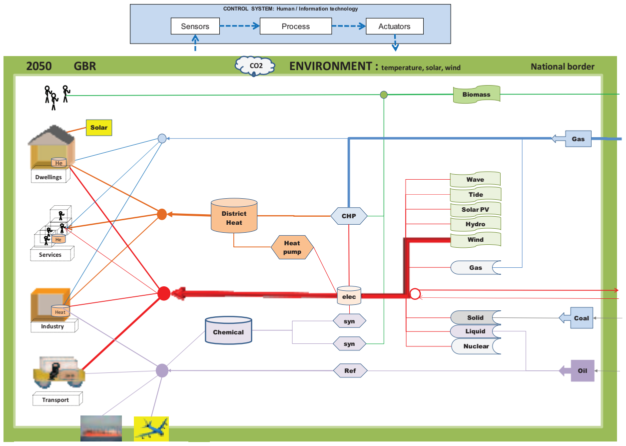


Figure 1. Whole Energy System Modelling - DynEMo.

On the left of the diagram are demand sectors: food, domestic, services, industry, national transport, international shipping and aviation. Apart from food, demands are divided into three stationary sectors and three transport sectors. In each sector, service demands, which includes motive power, lighting, water and space heating, process and cooling as they vary with the activity patterns of people and weather are modelled for each time step. Each of the stationary sectors includes a dynamic building model accounting for heat loss factors, internal gains and occupancy. Transport demand for passenger (passenger km) and freight (tonne km) (road, rail) is divided between modes (road, rail etc.) and vehicle technologies including electric vehicles. End use energy conversion technologies including solar and heat pump technologies and heat storage are included and each stationary end use sector (domestic, services, industry) has a heat store and electric vehicles have a battery store.

On the right of the diagram are the primary inputs to the system: chemical energy (biomass, coal, oil, gas), nuclear fuels and renewable electricity (tide, solar, hydro, wind). Solar heating is calculated in end use sectors. Three principal public energy supply systems converting primary energy into secondary energy are included: (i) electricity: renewable electricity and conversion of fossil and nuclear fuels to electricity and electricity storage (pumped storage); (ii) conversion of electricity and biomass to synthetic chemical fuels (hydrogen, ammonia, biofuels) and chemical fuel store; (iii) district heating with gas and biomass CHP and electric heat pumps as heat inputs, and a heat store. The system operates within an environment defined by ambient temperature, solar radiation, wind speed, tidal flow and wave intensity.

DynEMo energy comprises some 620 variables and 350 equations used in simulation and optimisation. DynEMo models components with different processes: weather, people, buildings, heat pumps, district heating etc. Due to the large number of equations only the general ones are described in this paper. More documentation of the model is provided on the UCL website [4].

DynEMo automatically generates about 100 charts. Time settings and input data can be changed without rebuilding the model to quickly give new results, and with the graphing this facilitates the rapid exploration of different systems under different weather conditions. The resultant model runs fast, 576 time periods takes about 0.5 seconds on a laptop.

III. MODEL COMPONENTS

Five basic parts of the system are modelled: environment, demands for services, energy conversion, storage, secondary supply, and primary finite and renewable primary energy supply. The scenario context and summaries of core equations and sample output are given below.

A. *Scenario Assumptions*

Assumptions about a future (nominally 2050) system are made with interpolations for intermediate years between 2010 and 2050. A scenario is defined by six sets of assumptions concerning user drivers (UDr), behaviour (UBe), technical efficiency (UEf), end use supply mix (USu), public supply efficiency (PEf) and public supply mix (PSu). As an example, Fig. 2 shows the assumptions made for population (Pop_M), household size (HHSize) and number of households (HHNum_M).

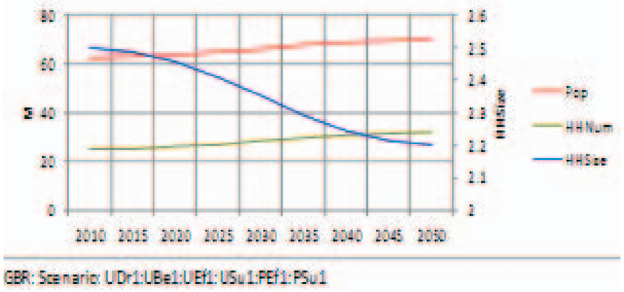


Figure 2. Scenario - demography.

B. *Energy System Controls*

The control system of an energy system comprises the following elements:

i. Sensors, human and technological, collect information about the current status of the environment, consumers, energy system technologies and trading partners.

ii. Strategy formulation. The sensor information, along with data on historical consumer activities or weather conditions, which is then used by information technology processes to devise control strategies to operate the system in future time periods.

iii. Strategy implementation. The final stage is for the devised control strategy to be expressed through actuators to physically control the system in the present.

Different algorithms are used to control electrically connected stores in and multi-fuelled systems (e.g. heat pump or CHP input to district heating) according to current and projected demands, renewable supplies and storage levels.

Two types of system control algorithms have been developed in the model. The first algorithm developed has a global system signal (GSS), analogous to a cost signal, quantifying the projected excess of renewable supply over demand over some period in the future. The GSS makes all stores increase input when there is a renewable surplus, but it takes no account of the different characteristics of the stores and proximity to consumer, or the potential for multi-fuelling inputs such as for district heating. Consequently, a second, sequential allocation (SA) algorithm was developed which accounts for store characteristics, but does not use projected surpluses or deficits. In this algorithm, an uncontrollable supply surplus is sequentially allocated to stores according to store size and the availability of multi-fuelling: in the system modelled, the order is domestic heat stores, electric vehicles, services and industry heat stores, district heat stores, synthetic fuels and electricity system storage (e.g. pumped storage). If all demands are met and stores or input capacities are full, any remaining surplus is exported or spilled.

C. Energy Demands

Energy demands are disaggregated into four sectors: domestic, services, industry and transport. For each sector or subsector, the time varying service demands are calculated. S(t) represents the demand for an energy service (motive power, appliances, process energy, light, heat, cooling) at any time t. It is dependent on human activity index, U(t) which is a multiplicand of hourly (h), weekday (w) and monthly (m) profiles and Unorm which normalizes U(t) to one across the year:

$$U(t) = U\,(h)\;U\,(w)\;U\,(m)\;U_{norm} \tag{1}$$

Some demands are almost weather independent, such as computing. For a weather independent demand, if the annual average demand (S_a), then S(t) is:

$$S\,(t) = S_a\;\;U\,(t) \tag{2}$$

Some services (space and water heating, space cooling, and lighting) are also functions of weather W(t):

$$S\,(t) = f\,(U\,(t),\,W\,(t)) \tag{3}$$

and some service demands are also functions of building (or vehicle) characteristics B(t):

$$S\,(t) = f\,(U\,(t),\,W\,(t),\,B\,(t)) \tag{4}$$

1) Energy Demands- Dwellings

For dwellings, various occupancy periods could be specified, for example from 7 am to 8 am and 5 pm to 11 pm. The control of building heating and cooling systems is an important determinant of the delivered energy load temporal profile, and this has a large impact on the upstream energy subsystems.

The temperature of the building $T_{b(t+1)}$ (^oC) at the start of the next period is calculated from the net heat flow into the building and the themal capacity B_c(Wh/K) of the dwelling:

$$T_b\,(t+1) = T_b\,(t) + (B_{hn}\,(t) + B_{ha}\,(t))\;\Delta t/B_c \tag{5}$$

where, $B_{ha}(t)$ (W) is the heating power to be added (heating) or substracted (if cooling is available).

The following charts depict the energy demands in the four principal sectors – domestic (D), industry (I), services (S) and transport (T).

Fig. 3 shows the heat flows into a dwelling: the incidental gains from hot water (DHWIncGain_W), appliances (DApp_W), occupants (DOccGain_W) and passive solar (DSolPassGain_W), and the residual required heat from the heating system (DSpEmit_W) as the demand varies with ambient temperature (Tamb_C) and the required comfort control temperature. The dwelling temperature, assumed to be that of the thermal mass, varies accordingly. It is brought to near the control temperature (DTContMax_C) which is the comfort temperature on the winter morning, maintained during active occupancy, and then allowed to subside in the winter night to the minimum set temperature, 16 °C in this case.

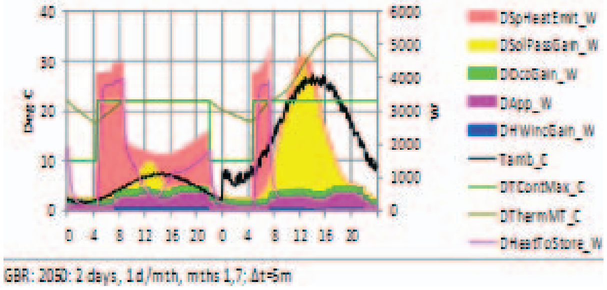


Figure 3. Domestic energy flows and temperature.

On the summer day, internal temperature rises above the comfort temperature; DynEMo only models air conditioning in service sector buildings and does not yet simulate loss modification to reduce overheating such as opening windows. The heat input to storage is DHeatToStore_W.

The interplay between ambient temperature (Tamb_C), storage temperature (DHeatStoreT_C) and heat pump coefficient of performance (DHPCOP) is shown in Fig. 4.

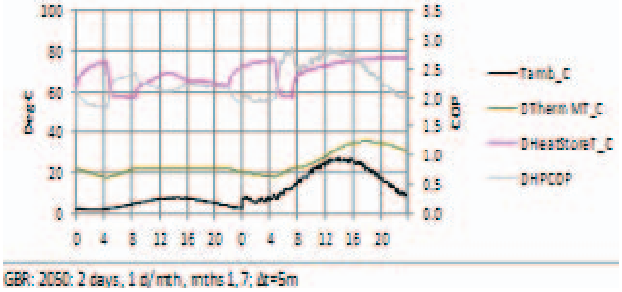


Figure 4. Domestic storage and heat pump COP.

As the difference between storage and ambient temperatures increases, the COP falls. It can be argued that heat pumps should be run continuously with low temperature output to maximise COP, but then space heat demand would be greater as the average building temperature is higher, and the heat pump cannot be turned on and off to take advantage of low cost, low carbon electricity.

2) *Energy Demands- Industry and Services Demands*

For the industrial sector (I) Fig. 5 shows: demands for liquids (Liq_GW), space heat (SpHeat_GW), process heat (ProHeat_GW), process chemical (ProChem_GW), process electricity (ProEle_GW), the heat store temperature (HeatStore_C) and heat pump COP (HPCOP). Space heating is proportionately small in the industrial sector so weather dependency is lower than the other stationary sectors.

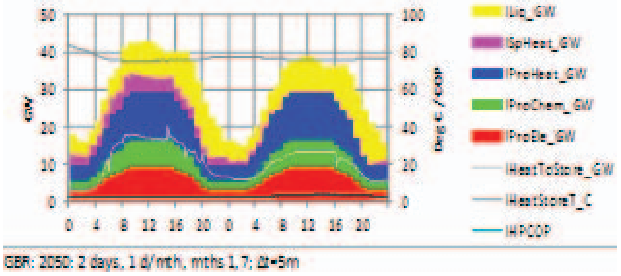


Figure 5. Industry demands.

For the services sector Fig. 6 shows: cooling (SpCool_GW), space heat (SpHeat_GW), hot water heat (HWHeat_GW), lighting (LightEle_GW), equipment electricity (EqEle_GW), and the cooling heat pump COP (HPCoolCOP). We see how the load changes from space heating to space cooling from winter to summer. Also notable is the change in lighting load.

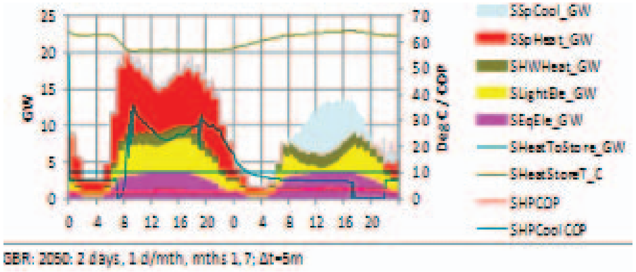


Figure 6. Services demands.

3) *Energy Demands- Transport*

Electrified transport is divided into rail (Trail_GWe), and electric vehicles battery output (TEVBattOut_GW), input (TEVBattIn_GW), and storage level (TEVBatt_GWh) as shown in Fig. 7. There is a slightly higher demand in winter than summer because vehicle passenger cabin heating is greater than cooling. Trail_GWe and TEVBattOut_GW follow the typical diurnal pattern of traffic flow.

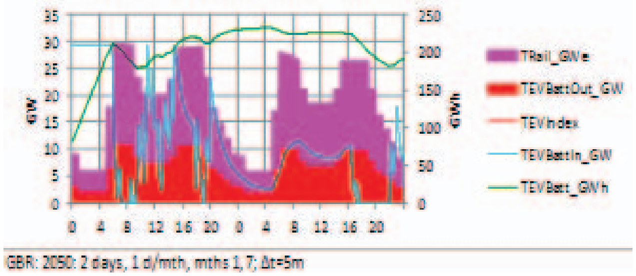


Figure 7. Transport (electric).

D. *Secondary and primary energy supply*

DynEMo models three secondary fuel systems: synthetic chemical fuels, heat and electricity.

1) *Synthetic chemical fuels*

Chemical fuel is synthesised for the transport sector using electricity or biomass. Currently synthetic fuel is not separated into different types such as hydrogen or ammonia.

Fig. 8 shows the operation of the synthesis: the amount synthesised and put into store (LiwSynIntoStore_GW), the electricity required (LiqSynEleInp_GW), the output (LiwSyn_GW), and the resultant storage level (LiqStore_Gwh).

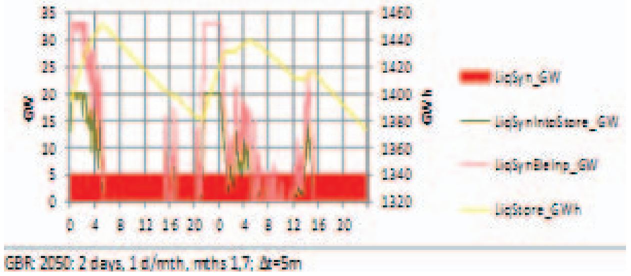
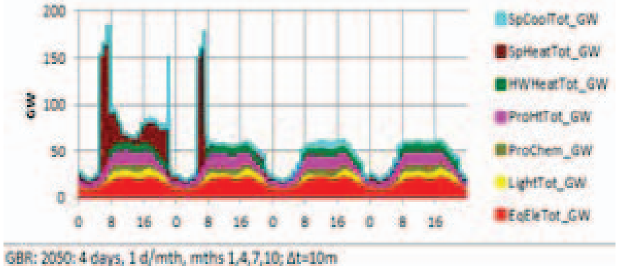


Figure 8. Chemical fuel synthesis.

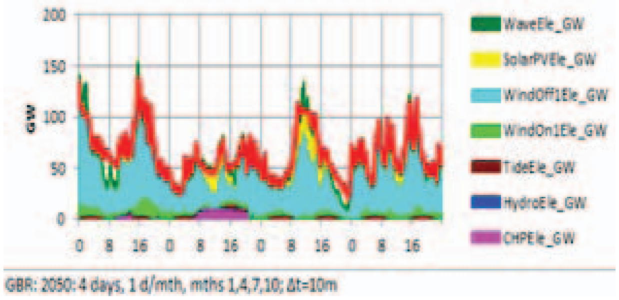
2) *Electricity*

Assuming no control through service demand change, electricity demand can be divided into an uncontrollable demand (EleDelUnc) comprising demands such as computing and a component that is controllable through end use storage or multi-fuelling. Electricity supply can be divided into uncontrollable renewable generation EleRenUnc (wind, solar, wave, tide) and controllable supply using stored fuels (biomass, fossil). Nuclear is assumed non-dispatchable. If EleDelUnc is greater than EleRenUnc, energy has to be taken out of artificial storage, or dispatchable generation used, or electricity imported; and vice versa. Dispatchable fossil generation is brought on line in the fixed order gas, coal, oil and electricity trade depending on surplus, deficit and relative costs. The electricity control strategy is illustrated in the following five Figures. First we have the demands for useful energy summed across all sectors (Fig. 9), followed by the supply of variable renewable and CHP electricity, heat demand and storage (Fig. 10).



GBR: 2050: 4 days, 1 d/mth, mths 1,4,7,10; Δt=10m

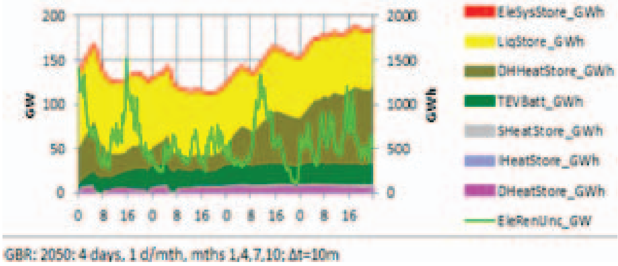
Figure 9. Useful energy demands.



GBR: 2050: 4 days, 1 d/mth, mths 1,4,7,10; Δt=10m

Figure 10. Renewable and CHP electricity supply.

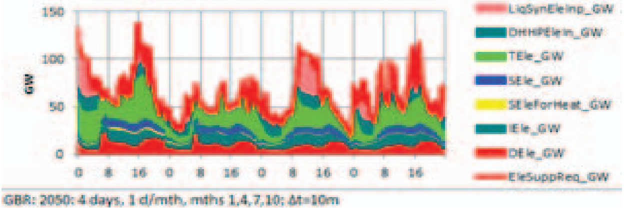
Fig. 11 shows the changing levels of electrically connected storage to modify electricity consumption to better match uncontrollable renewable (EleRenUnc) and CHP generation (CHPEle) shown in Fig. 10.



GBR: 2050: 4 days, 1 d/mth, mths 1,4,7,10; Δt=10m

Figure 11. Energy Storage.

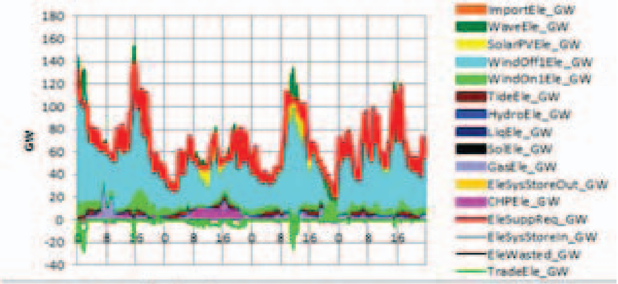
Note the relative sizes of the different stores assumed. Fig. 12 shows the storage modified electricity consumption for the end use sectors (D, I, C, T) and for secondary energy production – for district heating heat pumps (DHHPEleIn) and chemical synthesis (LiqSynEleInp). The low position of the synthetic liquid store in the *SA* control merit order is shown by the extreme variation in LiqSynEleInp as compared to the other storage modulated demands.



GBR: 2050: 4 days, 1 d/mth, mths 1,4,7,10; Δt=10m

Figure 12. Modified electricity consumption.

All demand and supply is shown in Fig. 13. Where there is a deficit of supply, dispatchable gas (GasEle) or imports (TradeEle) are used. When there is excess, it is exported (TradeEle) up to the trade link capacity (30 GW assumed in 2050); any remaining surplus is wasted (EleWasted).

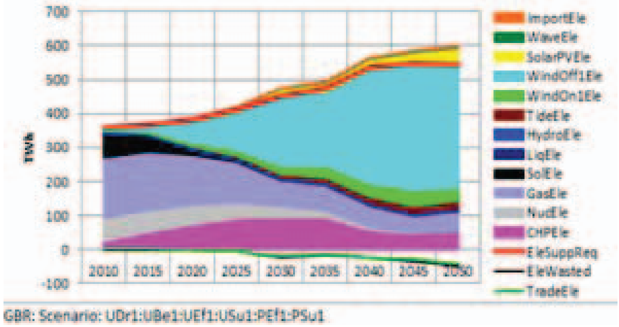


GBR: 2050: 4 days, 1 d/mth, mths 1,4,7,10; Δt=10m

Figure 13. Electricity demand, supply and trade.

IV. ANNAUAL TEMPORAL AGGREGATION

The simulated flows over minutes are aggregated to monthly and annual flows. In here we provide examples of annual temporal aggregation. In Fig. 14 is shown the major shift from gas and liquid fuel deliveries to heat and electricity.



GBR: Scenario: UDr1:UBe1:UEf1:USu1:PEf1:PSu1

Figure 14. Scenario electricity supply.

Because of the greater efficiency of heat pumps and district heating in the end use sectors, deliveries decline faster than useful energy demands. These aggregations of short step dynamic modelling demonstrate interactions between demand, supply and storage that are not handled by models with coarser temporal definition.

Fig. 15 shows the substantial replacement of fossil and nuclear generation with renewables (mainly wind), but the short period dynamics are such that renewable energy deficits and excesses still occur and increase in size so that dispatchable gas generation is still needed even though exports increase. CHP production (which includes industrial CHP) increases as district heating is integrated in the system, but then declines as more renewable electricity becomes available to drive district heating heat pumps.

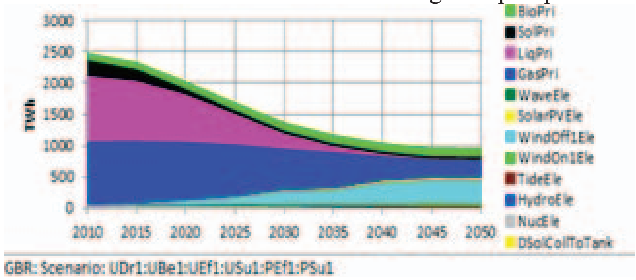


Figure 15. Scenario primary energy.

Annual primary energy reduces to about half of current consumption by 2050 as shown in Fig. 15. This is due to the energy efficiency; the gross trend is for fossil liquid and gas is to be replaced by wind.

V. CONCLUSIONS

The society and energy systems are interconnected. Static or coarse temporal modeling and an oversimplified account of the interplay between people, weather and energy will not provide a basis for the design of robust systems – to the degree that some proposed systems may not function technically in certain conditions. The DynEMo model investigates how society engenders time and climate varying energy service demands in the different sectors (domestic, commercial, industry and transport) and how different forms of energy resources, can meet these demands over different time scales. The model might be extended to industrial waste heat utilization in district heating, district cooling, the use of synthetic fuels for dispatchable generation and carbon sequestration. A significant challenge is the system boundary; in particular, quantifying the potential for international electricity trade would require the dynamic modeling of several interconnected regions and optimizing trade, which poses a significant modeling and data challenge.

ACKNOWELDGEMENTS

The authors would like to thank the sponsors for their support: The Engineering Physical Sciences Research Council (EPSRC) and EDF Energy part of the project “People Energy and Buildings: Distribution, Diversity and Dynamics” (EP/H051112/1) which is being undertaken in partnership with EDF European Energy Efficiency Research Centre (ECLEER).

REFERENCES

[1] AN. Andersen, H. Lund, “New CHP partnership offering balancing of fluctuating renewable electricity productsions,” Journal of Cleaner Production, vol. 15 (3), 2007, pp. 288-293, doi:10.1126/science.1065467.

[2] M.A. Barrett, “Dynamic Physical Energy Model of the United Kingdom”, PhD thesis, Open University, 1981, Available online: http://www.societyenergyenvironment.net/Energy/Dynamic%20model/MBarrett%20DYPHEMO%20ERG045.pdf

[3] M. Barrett, C. Spataru, “Optimizing Building Energy Systems and Controls for Energy and Environment Policy”. In Anne Håkansson, Mattias Höjer, Robert J. Howlett, and Lakhmi C. Jain (Eds.), *Smart Innovation, Systems and Technologies, Sustainability in Energy and Buildings* 2013: 413-425. Berlin Heidelberg: Springer-Verlag

[4] M. Barrett, C. Spataru, “DynEMo documentation”, Available online: http://www.ucl.ac.uk/energy-models/models/dynemo

[5] Enerdata, “POLES: Prospective Outlook on Long Term Energy Systems”, 2010. Available online http://www.enerdata.net/enerdatauk/tools/Model_POLES.htmlS

[6] ETSAP, “MARKAL”. Available online http://www.iea-etsap.org/web/Markal.asp

[7] IAEA (International Atomic Energy Agency), “PESS Energy Models”, 2010. Available online http://www.iaea.org/OurWork/ST/NE/Pess/PESSenergymodels.shtml S

[8] R. Loulou, G. Goldstein, K. Knoble, “Documentation for the MARKAL Family of Models”. Energy Technology Systems Analysis Program (ETSAP), 2004. Available online: http://www.etsap.org/MrklDoc-I_StdMARKAL.pdfS

[9] R. Loulou, M. Labriet, “ETSAP-TIAM: the TIMES integrated assessment model part I: model structure”, Computational Management Science , vol. 5, 2007; pp. 7-40.

[10] H. Lund, AN Andersen, PA Østergaard, BV Mathiesen, D. Connolly “From electricity smart grids to smart energy systems e a market operation based approach and understanding”. Energy, vol. 42 (1), 2012; pp. 96-102.

[11] H. Lund, “EnergyPLAN Advanced Energy Systems Analysis Computer Model Documentation” Version 11.4 Aalborg University Denmark, Available online http://www.energyplan.eu/wp-content/uploads/2013/06/EnergyPLAN-Documentation-V11.4-2014.pdf

[12] National Grid, 2013. Available online: http://www.nationalgrid.com/NR/rdonlyres/332FFA28-6900-4214-92BB-D3AD4FA5DC01/56611/UKFutureEnergyScenarios2012.pdf

[13] National Grid, “UK Future Energy Scenarios”, 2012. Available online: http://www.nationalgrid.com/uk/Electricity/MajorProjects/EnergyChallenge.htm

[14] NTUA (National Technical University of Athens), “The Primes Energy Systems Model, 2010”. Available online: http://www.e3mlab.ntua.gr/manuals/PRIMsd.pdfS

[15] A. Pina, “Modeling Supply and Demand Dynamics in Energy Systems Planning”, MIT Portugal Available online: http://web.mit.edu/mppgreenislands/gip/Workshop_Presentations_files/32b_Pina_Integrated_Energy_Modeling.pdf

[16] Van der Voort, “The EFOM 12C energy supply model within the EC modelling system”. Omega, vol. 10 (5), 1982, pp. 507-523.