Network reinforcement requirements for Scotland and the rest of the UK (RUK) – and possible solutions for this

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A novel multi-objective transmission expansion planning (MOTEP) tool has been developed to analyse, on a comprehensive geographical scale, the reinforcements required to a base case electrical transmission network following application of a chosen future energy scenario, and to generate optimal network expansion plans, designed to alleviate these areas of strain, for a range of crucial network planning objectives. Here, we report the application of the MOTEP tool to a base case predicted 2014 GB transmission network (thereby including already planned reinforcements such as the Beauly to Denny line) under heavy strain from three 2020 energy scenarios developed by the two-region UK MARKAL energy system model. Reinforcement requirements for Scotland and the RUK beyond 2014, along with optimal network expansion plan options, are examined.

A snapshot of the current situation of the GB transmission network

At present the GB transmission network is under strain where there are no generation connection opportunities in Scotland, Wales or the North of England (National Grid, 2009) and as such there is a need for major transmission reinforcement in these areas. The predominant power flow in mainland GB is from net generation in the North (Scotland) to net demand in the South (England) and this is going to increase as wind farms are connected in the North where there is a more abundant fuel source. This net southerly flow is currently across transmission circuits that are already operating at their maximum capability (ENSG, 2009), hence, the GB transmission network needs to be reinforced and expanded to accommodate increased renewable generation penetration needed to achieve the CO_2 emissions target of a 34% reduction by 2020. Parallel to the emissions objectives, for 2020 and 2050, future network developments need to be planned optimally in order to reduce grid connection charges and consumer electricity bills.

Construction has already begun on the crucial 220km, 400kV, 4740MVA capacity overhead line between Beauly and Denny in Scotland with expected completion in 2014. This is a major reinforcement to enhance network capability for the future connection of renewable energy in the North of Scotland (6,176MW capacity of accepted renewable generation is awaiting the inclusion of the Beauly to Denny line for grid connection (Scott, 2009)). Although the inclusion of this reinforcement, along with other planned reinforcements by 2014, greatly alleviates network strain, there is no cast iron network plan beyond 2014 to achieve the 2020 emissions target.

The newly developed MOTEP tool is implemented here for three 2020 scenarios; the low carbon scenario (LCS), the renewable energy directive scenario (RED) and the RED scenario including the Scottish 100% renewables target (RED & 100%). The generation mix for each scenario was generated via the two-region UK MARKAL model.

The MOTEP tool

The MOTEP tool has recently been developed to apply a future electricity supply generation mix to a base case transmission network for creation of an optimal set of expansion plans to resolve predicted areas of network strain. Each expansion plan is evaluated against five key objectives in transmission planning for analysis into the objective trade-offs of each plan. Over successive generations of optimisation inside a genetic algorithm, expansion plans are created before being assessed on these objectives for whether each plan can continue into the next generation of solutions or be scrapped due to poor fitness in relation to the other plans. The MOTEP tool therefore uses an iterative optimisation process until a final set of expansion plans is obtained where each plan on this set is optimal, for the multi-objective problem, in its own unique way. This complex multi-objective optimisation, among often conflicting goals, is preferred to a linear cost optimisation for better understanding of the problems likely to be faced in the future, and the difficult decisions required to be made in regard to these trade-offs. Further multi-objective analysis allows for trade-offs to be made between cost and non-cost objectives. The five key objectives chosen for plan evaluation are:

- Network Investment Cost (total capital cost of the transmission plan using build and upgrading costs);
- Network Constraint Cost (total constraint costs saved by the transmission plan under peak and base demand conditions using an optimal market analysis program);
- Outage Cost (total cost of outages needed to accommodate the plan construction);

- Transmission Losses (MW's saved from 'variable' I2R heating losses); and
- Minimum CO2 emissions intensity (from a network capability assessment of each plan's ability to cope with increasing levels of renewable generation).

The MOTEP tool is novel in its use for full spatial analysis of a realistic multi-voltage transmission network. Due to the large scale network base case used, the MOTEP tool employs a static DC power flow simulation of the network at peak demand. This means that the focus of MOTEP lies with active power planning where each expansion plan generated must adhere to thermal line limits (MVA line capacity) but not to voltage and reactive power limits associated with an AC power flow. Due to the study occurring at peak demand, this also means that each generated plan must adhere to the deterministic security criterion of N-1 (loss of one circuit component) and N-D (loss of a double-circuit component).

The MOTEP tool is also novel in its creation of a transmission expansion plan. The MOTEP tool includes two methods for reinforcement and/or expansion of a thermally overloaded line. The first method is through the addition of a line by adding either a single circuit or double circuit configuration. The second method is by upgrading the existing line through re-conductoring, adhering to pre-defined voltage level line capacity limits. The inclusion of line upgrading in the plan creation process is crucial to allow a minimum capital investment cost for each generated expansion plan to be achieved due to the reduced associated cost of re-conductoring compared to line addition.

More details regarding the MOTEP tool are contained in a paper that is currently being reviewed for publication in an academic journal.

Results: Areas of network strain under all three scenarios and optimal expansion plan solutions

Here the three scenarios of LCS, RED and RED & 100% are applied to a predicted 2014 GB transmission network base case that includes the Beauly to Denny line amongst other expected network reinforcements and expansions. A maximum line load condition that a power flow must not exceed before being treated as an overload was set to 84% of the line capacity. This line load condition percentage was determined from a DC power flow peak demand study of the 2009 GB transmission network. It was found that no power

Table 1: Shows the location and severity of thermal overloads for each scenario as modelled by MOTEP The zones refer to Figure 1

Zone	Line (node 1 – node 2)	Overhead Line / Underground Cable Length (km)	Voltage (kV)	Line Capacity (MVA)	Overload Percentage (%)
LCS Scenario base problem					
5	442 – 739	5.72 / 0	132	132	103.87
9	222 – 262	11.32 / 0.32	400	2090	86.97
15	36 – 782	18.69 / 0.5	275	860	90.55
18	276 – 781	34.91 / 0	400	1560	84.32
RED Scenario base problem					
5	442 – 739	5.72 / 0	132	132	97.15
9	222 – 262	11.32 / 0.32	400	2090	85.03
11	657 – 898	35.78 / 0.17	400	1160	100.54
13	897 – 898	0 / 5.71	400	1220	95.59
13	818 – 897	9.94 / 0.43	400	1160	100.54
14	685 – 755	43.3 / 0	400	2150	84.74
15	36 – 782	18.69 / 0.5	275	860	89.36
RED & 100% Scenario base problem					
4	658 – 871	0 / 3.7	132	120	84.85
5	442 – 739	5.72 / 0	132	132	117.59
11	657 – 898	35.78 / 0.17	400	1160	98.56
13	897 – 898	0 / 5.71	400	1220	93.72
13	818 – 897	9.94 / 0.43	400	1160	98.56
15	36 – 782	18.69 / 0.5	275	860	85.6

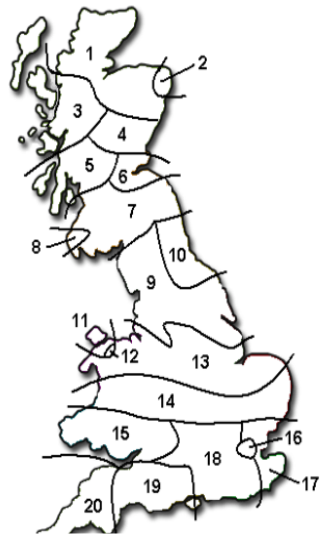

Figure 4. Generation use of system tariff zones used in 2009.

flow exceeded 84% of the associated lines capacity, therefore this was set as the condition required of the GB transmission network in 2020. The areas of network strain determined by MOTEP for all three scenarios are detailed in Table 1.

It appears from Table 1 that the LCS scenario requires the least network reinforcement of all three scenarios with only 4 lines failing the pre-set line load condition. The RED and RED & 100% scenarios require a similar level of reinforcement (RED has one more overload), however the RED & 100% scenario requires two reinforcements in Scotland as opposed to just one. All other network reinforcement requirements are located in central England and in the North and South of Wales. The Welsh overloads are due to the predicted location of new onshore wind farm developments in these areas, added to achieve RUK scenario targets. It is clear from Table 1, when observing the severity of the overloads and the length of these strained lines, that there is not a significant amount of reinforcement required to the 2014 GB transmission network in order to cater for the three 2020 scenarios. Nonetheless, a multi-objective optimisation was carried out by MOTEP to locate and assess a set of optimal network expansion plans for all three scenarios. Allowance was made for the possibility of connecting a double-circuit line and a single-circuit line to an existing route, enabling a wide range of line addition/upgrade combinations for each thermally overloaded line, thereby enabling the exploration of a wide range of expansion plans.

All generated expansion plans are designed to fully eliminate 2020 network constraint costs at peak demand for all three scenarios. MOTEP has calculated that during a one hour simulation at peak demand in 2020 a constraint cost saving of £725 for the LCS scenario, £1219 for RED and £3288 for RED & 100% can be achieved by full reinforcement. The extent of this saving (particularly for the RED & 100% scenario) under this one hour operational setting, provides a good further incentive for continued network expansion beyond 2014 when considering the lifespan of new transmission assets. The constraint cost at base demand was found to be zero for all three scenarios, without the need for reinforcement. Hence the base demand constraint cost could not be included in the multi-objective analysis. Figure 2 details the output from the multi-objective analysis of the most demanding scenario RED. Table 2 shows the most interesting optimal expansion plans from this multi-objective analysis.

Figure 2: The multi-objective analysis output of the RED scenario as modelled by MOTEP

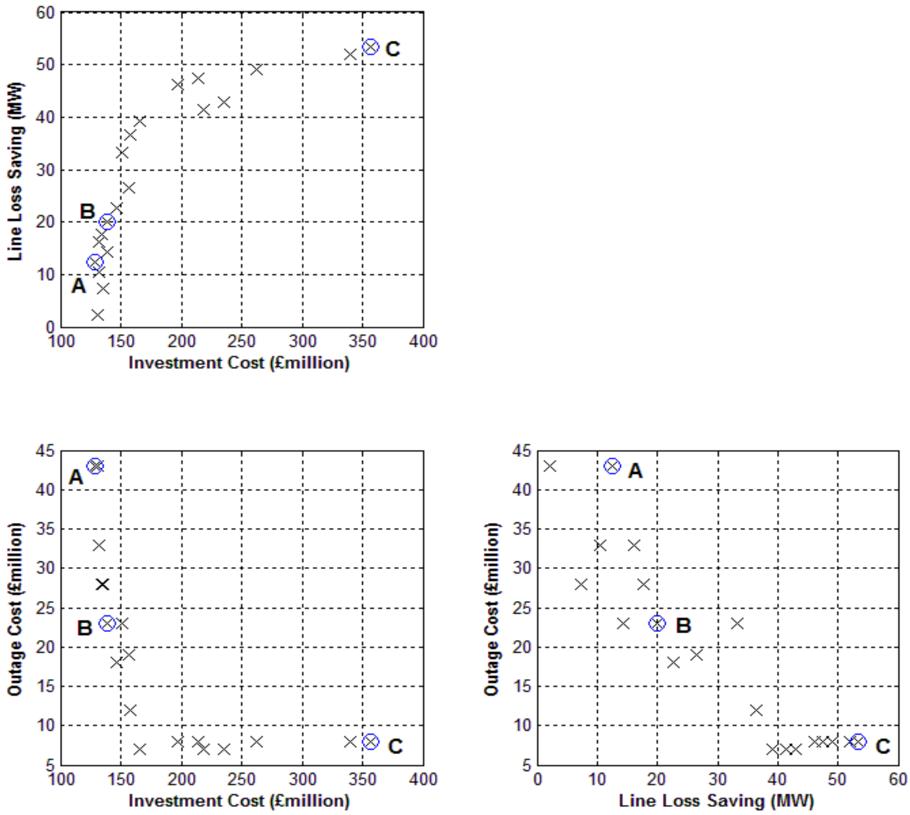

Table 2: Shows the three most interesting optimal expansion plans from the multi-objective analysis detailed in Figure 2. The circuit layout of the plan along with the objective evaluations is detailed

Expansion Plan	No. of Double-circuits / Single-circuits / Upgrades	Capital Investment Cost (£million)	Outage Cost (£million)	Line Loss Saving (MW)	Minimum CO2 Emissions Intensity (g/KWh)
A	2 / 1 / 4	128.54	43	12.44	320.47
B	4 / 1 / 2	138.72	23	19.96	274.89
C	5 / 4 / 1	356.42	8	53.34	314.88

From table 2 it is clear that expansion plan B is a good option for the RED scenario. Expansion plan A has the lowest investment cost but comes with a large outage cost. The increase in around £10 million in capital investment for plan B comes with a £20 million reduction in outage cost from plan A. Further plan B has a low CO2 emissions intensity, according to the objective evaluation, which suggests a good location of transmission assets for future grid connection of large scale renewable generation.
Concluding Statements from the MOTEP tool analysis

MOTEP's analysis shows that only one reinforcement, on a small 6km overhead line, is required beyond 2014 for Scotland's electrical transmission network to cope with the 2020 LCS and RED scenarios. An added reinforcement on a 4km underground cable is required for application of the RED & 100% scenario. All other expansion requirements are located in central England and southern Wales. The minimum capital investment cost required for an expansion plan, to eliminate thermal overloads and maintain current deterministic security criterion, for the RED scenario is £128 million. This is around 3 times greater than the minimum capital cost of an expansion plan for the LCS scenario. It is clear that according to the MOTEP tool simulations, all three 2020 scenarios require minimal network reinforcement beyond the predicted 2014 GB transmission network. The largest capital investment for an expansion plan occurred in the LCS scenario simulations; £475.5 million. This would still represent a modest investment on top of the now predicted £600 million capex for the proposed Beauly to Denny line. This is due to the short line route lengths and low thermal line ratings of the new MOTEP proposed lines for required expansion beyond 2014. The longest and largest line requiring reinforcement, which occurs under the RED scenario (see Table 1), is a 43.3km line rated at 2150MVA. This is over half the capacity rating of the proposed Beauly to Denny line and a fifth of the line length.

References

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