Preprint Cambridge Centre for Computational Chemical Engineering ISSN 1473 – 4273

A nuclear future? Small Modular Reactors in a carbon tax-driven transition to clean energy

Wanni Xie[1], John Atherton[1,2], Jiaru Bai[1], Feroz Farazi[1], Sebastian Mosbach[1,2], Jethro Akroyd[1,2], Markus Kraft[1,2,3,4]

released: July 27, 2023

[1] Department of Chemical Engineering
and Biotechnology
University of Cambridge
Philippa Fawcett Drive
Cambridge, CB3 0AS
United Kingdom

[2] CARES
Cambridge Centre for Advanced
Research and Education in Singapore
1 Create Way
CREATE Tower, #05-05
Singapore, 138602

[3] School of Chemical
and Biomedical Engineering
Nanyang Technological University
62 Nanyang Drive
Singapore, 637459

[4] The Alan Turing Institute
2QR, John Dodson House
96 Euston Road
London, NW1 2DB
United Kingdom

Preprint No. 312

UNIVERSITY OF CAMBRIDGE

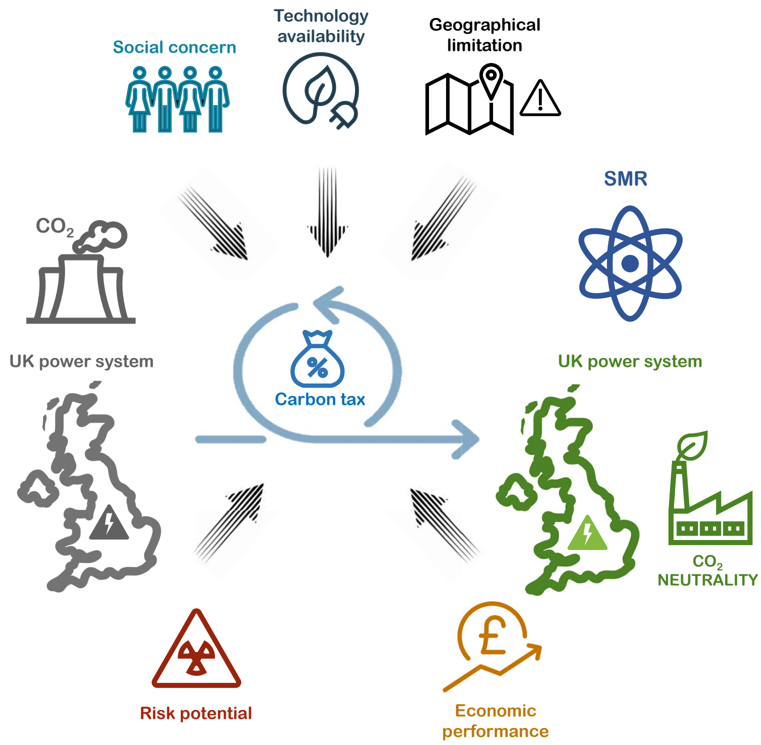
Keywords: Small Modular Reactors (SMRs), Carbon tax, Placement policy, Clean energy transition, Fossil fuel replacement, Electrical power generation

Edited by
Computational Modelling Group
Department of Chemical Engineering and Biotechnology
University of Cambridge
Philippa Fawcett Drive
Cambridge, CB3 0AS
United Kingdom

E-Mail: mk306@cam.ac.uk
World Wide Web: https://como.ceb.cam.ac.uk/

Abstract

The study investigated the effect of a CO_2 tax to encourage the adoption of Small Modular Reactors (SMRs) as an alternative to fossil fuels for power generation in the UK. The trade-offs of different SMR placement policy options with respect to the competing objectives of minimising transmission losses and population risk were investigated. Different assumptions about renewable power availability were explored. The study identified the most cost-effective number of SMRs per site. Regardless of renewable power availability, a carbon tax in the range £45–60/t was found to incentivise the full adoption of SMRs with a levelised cost of electricity of £60/MWh versus £0–20/t at £40/MWh. The SMR placement influenced the performance and cost of the energy system, as well as whether a region acted as a net importer or exporter of energy. The most cost-effective solutions were achieved by balancing transmission loss and population risk.



Highlights

- Investigated carbon tax to motivate adoption of small modular reactors (SMRs)
- Data-driven investigation of policy trade-offs for placement of SMRs
- Pareto front between objectives to minimise risk and transmission loss
- Identified regions for possible placement of SMRs

Contents

1 Introduction

Climate change caused by greenhouse gas emissions is a global problem. Electric power generation accounts for approximately 16% (53.7 $MtCO_2e$ in 2022) of greenhouse gas emissions in the UK [36]. The corresponding energy mix consisted of fossil fuels (41.5% natural gas, 1.6% coal), conventional nuclear power (16.7%), wind (28.8%), solar (4.6%), hydroelectricity (1.2%) and biomass (5.6%) (2022) [19, 31]. The UK must replace fossil-fired power generation with low-carbon alternatives if it is to cut emissions [36]. It must simultaneously accommodate a projected 50% increase in power demand by 2035, driven by support for electric vehicles, heat pumps, and hydrogen [8]. It aims to achieve 95% low-carbon power generation by 2030, and to reduce the emission intensity of power generation to less than 5 gCO_2/kWh by 2035, compared to 182 gCO_2/kWh in 2022 [8, 33].

Different forms of carbon tax have been introduced to incentivise the development and deployment of low-carbon technology [21, 26, 37]. The UK introduced a Carbon Price Floor (CPF) to support the EU Emissions Trading System (ETS) in 2013 [26]. The CPF taxes fossil fuels used for power generation. It consists of two components: an ETS allowance price and a Carbon Support Price that supplements the ETS allowance price to reach a target carbon price. The impact of carbon pricing and subsidies for renewable energy have been widely investigated. Mo and Zhu [30], for example, studied how to design a CPF to promote investment in carbon capture and storage (CCS). They estimated that a price of €20/t would stimulate investment, while €30/t would be required to sufficiently promote carbon abatement. More recently, Gugler et al. [24] compared the outcome of a CPF with subsidies for wind and solar power in the UK and Germany. Carbon pricing outperformed subsidies in their simulations, with a moderate tax (approx. €30/t) leading to a significant cut in emissions by incentivising the replacement of coal with natural gas.

The UK has outlined plans for the adoption of low-carbon energy technology. The recent 'Energy white paper' [38] and 'Ten-point plan for a green industrial revolution' [12] both identify offshore wind and nuclear power as crucial components of decarbonising power generation. Point 1 of the 'Ten-point plan' targets 40 GW of offshore wind capacity by 2030. This represents a substantial increase compared to current capacity (11 GW onshore, 12.7 GW offshore) [11]. Point 3 promotes the development of nuclear energy projects, including new large-scale plants, the deployment of small modular reactors (SMRs) and the development of advanced modular reactors (AMRs). This stands in contrast to a decrease in the annual share of electricity provided by nuclear power from 23% to 14.9% between 2000 to 2021 due to the decommissioning of ageing plants [29]. Currently, only six conventional nuclear plants with a combined capacity of 6.8 GW remain in operation in the UK [11]. By 2035, most of the remaining plants will have reached the end of their operational life, with only one new 3.2 GW European Pressurised Reactor plant currently under construction at Hinkley Point C. If no others are constructed, the nuclear capacity of the UK will be reduced to approximately one-third of its current level by 2050 [15, 25]. However, in 2022, the UK published a target to introduce up to 24 GW of new nuclear capacity by 2050, aiming to contribute approximately 25% of electricity generation. This represents a 3.5-fold increase in nuclear capacity compared to 2022 [8, 29, 41] and is consistent with the vision of the 'Ten-point plan', indicating a strong focus on developing nuclear capacity over the coming decades.

The UK performed a techno-economic assessment of small modular reactors (SMRs) in 2016 [14]. The analysis estimated the advantages to the UK economy and society, including £20 billion of undiscounted gross value added if 70% of supply chain components were manufactured in the UK between 2017 and 2040. Cárdenas et al. [7] examined the impact of nuclear power as a baseload component of a carbon-free electricity system in the UK. They showed that conventional nuclear plants would be expensive relative to renewable energy, but that SMRs showed promise in achieving cost-effective power generation by supplying approximately 80% of demand. Conversely, Asuega et al. [2] concluded that while SMRs do not exhibit significant economic benefits compared to large reactors in the UK, their advantage lies in the factory approach to production, which mitigates construction delays and cost overruns. Steigerwald et al. [40] investigated the uncertainties associated with estimating production costs for SMRs. They showed that SMRs may not be cost-effective, with no positive net present value observed over their lifespan, and estimated the mean Levelised Cost of Electricity (LCOE) for the 470 MW SMR prototype developed by Rolls-Royce as approximately 222 USD_{2020}/MWh. This is considerably more than the £40–60/MWh estimate published by World Nuclear News [44], the low end of which is similar to estimates of the future LCOE between 2030 and 2040 for wind (which is more abundant than solar) power in the UK [16].

The potential of SMRs outside the UK has also been studied. Nian et al. [34] examined the economic competition between nuclear (conventional and SMRs), wind and solar power in the context of replacing fossil-fueled power generation, providing insights into net-zero pathways for the Association of South East Asian Nations (ASEAN) countries. They proposed a life cycle analysis framework to assess the LCOE and total emissions, highlighting that the driving factor for nuclear power is to reduce carbon emissions by replacing fossil fuels. A team from the University of Regina have extensively investigated where to site SMRs in Saskatchewan, Canada. Gao et al. [22] proposed a factorial optimisation-based SMR siting (FOSS) method to choose where to site SMRs within a general electricity-system framework. They considered the competitive relationship between CCS and SMR and showed that replacing decommissioned coal-fired power plants with SMRs would contribute to at least 65.6% reduction in emissions by 2045, compared to a 2018 baseline. Gao et al. [23] extended the analysis to encompass all of Canada. The approach was modified by Zhang et al. [45] to integrate climate, economic and social factors to reflect the long-term effects of climate change to support site selection. Liu et al. [28] further extended the approach to identify patterns of SMRs and wind farm siting in Saskatchewan. The site selection algorithm was observed to give priority to power stations with large capacities and independent transmission grids.

While these studies raise questions about the economic performance of SMRs, the assessments vary depending on the system specifications and criteria chosen by researchers including the indicators used and the scope of analysis. Clearly, these issues contribute to the debate. Notwithstanding this, the 'Ten-point plan' [12] specifies a clear target for the introduction of up to 24 GW of nuclear capacity in the UK, with SMRs identified as a key part of the plan. Rolls-Royce is developing a 470 MW 'UK SMR', with an estimated capital cost (CAPEX) of £1.8 billion per SMR and an estimated LCOE of £40–60/MWh over a lifespan of 60 years [44]. In March 2022, the UK government begin a three-step generic design assessment of the Rolls-Royce SMR. The first step ran from April 2022 to March 2023 and agreed on the scope and schedule for technical engagements. The second step started in April 2023 and will perform a 16-month assessment of the fundamental acceptability of Rolls-Royce SMR design [6]. So far, Rolls-Royce has identified four potential sites for deployment of the SMRs, Trawsfynydd, Sellafield, Wylfa, and Oldbury [20].

A number of questions regarding the potential deployment of SMRs in the UK remain unaddressed. How many would be needed? Where would they be placed? Are the sites suggested above sufficient? Which fossil fuel plants should be replaced and in what order?

The **purpose of this paper** is to investigate what level of carbon tax would be required to incentivise the widespread adoption of SMRs and to estimate many SMRs would be required to replace fossil fuels for electrical power generation in the UK. We consider explicit carbon taxation, which directly assigns a monetary value to CO_2 emissions. The study demonstrates a systematic algorithm for the optimal siting of SMRs that takes into account the geospatial configuration of the existing transmission grid, and seeks to balance the trade-off between siting SMRs away from centres of population but close to areas of demand to minimise risk while maximising efficiency. It shows how different siting criteria impact cost, transmission losses and the energy independence of different regions, providing a framework to support future decisions.

2 Methodology

Fig. 1 shows the optimisation algorithm used to assess the cost and placement of the SMRs. For the purpose of this analysis, we consider SMRs with a capacity of 470 MWe at an estimated cost of £1.8 billion per unit, with scenarios for an LCOE of both £40/MWh and £60/MWh, based on the nominal specifications of the Rolls-Royce design [43, 44]. The analysis makes use of a 29-bus model of the UK high-voltage power transmission system [4]. The model consists of 29 buses, 99 branches and 1129 generators. The results presented in this study were obtained using the 29-bus model, and cross-checked using a 10-bus model [3] to verify that they were insensitive to the choice of model.

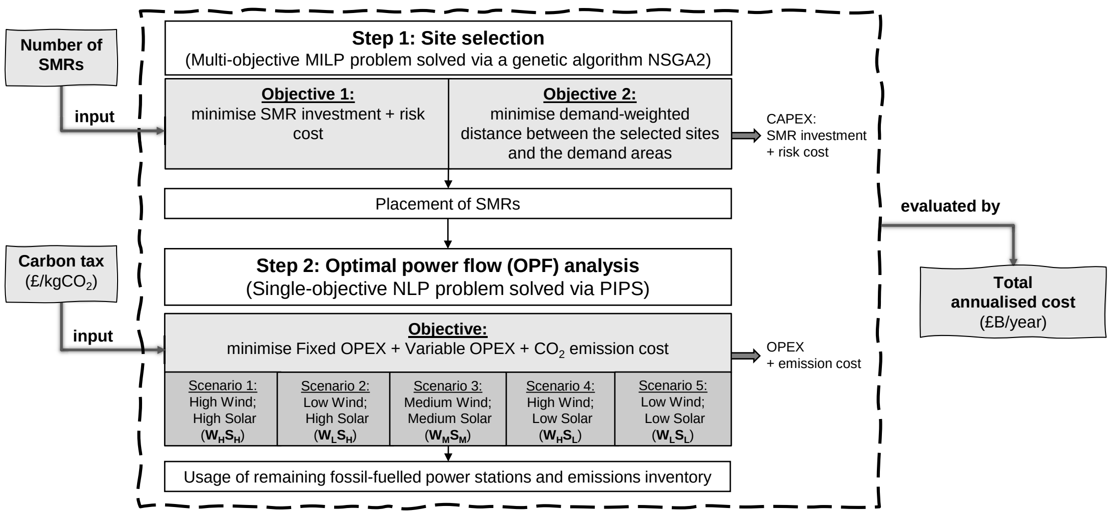


Figure 1: *Algorithm used to calculate the cost and placement of SMRs.*

The algorithm consists of two steps. The first step selects sites for the placement of SMRs. The number of SMRs is provided as an input. It employs the Non-dominated Sorting Genetic Algorithm (NSGA2) [5] to address two objectives. Objective 1 aims to minimise the capital expenditure (CAPEX) and risk costs associated with the placement of the SMRs, while objective 2 aims to minimise the demand-weighted distance between the SMRs and centres of demand. The distance metric serves as a proxy for minimising transmission losses and ensuring balanced grid operations. The demand is represented as a load on each bus of the transmission grid model. The candidate locations for the placement of SMRs were the sites of existing fossil-fuel (68), former fossil-fuel (8) and former nuclear (6) power stations. The optimisation was subject to the constraints that no more than four SMRs could be placed on a given site and that SMRs could not be placed on two sites that are in close proximity. The choice to frame the placement problem in this way ensures that the algorithm can only place SMRs in locations that have existing connections to the transmission grid. At each iteration, NSGA2 identifies a feasible solution expressed in terms of the location of each SMR, and the corresponding CAPEX and risk cost.

The second step samples the feasible solutions by taking the weighted sum of the two normalised objectives to give a single weighted objective. The choice of weight allows the exploration of the effect of different placement policy options. The annualised total cost is calculated for each sampled solution

$$C_{\mathrm{T}} = \frac{C_{\mathrm{CAPEX}} + C_{\mathrm{Risk}} + \sum_{l=1}^{L} \frac{C_{\mathrm{OPEX}} + C_{\mathrm{Emissions}}}{(1+d)^{l}}}{\frac{1-(1+d)^{-L}}{d}}, \tag{1}$$

where C_{T} represents the annualised total cost as a net present value divided by an annuity factor. C_{CAPEX} and C_{Risk} denote the CAPEX and associated risk cost. C_{Risk} is proportional to the population located within a given radius of each site selected to host SMRs, where the radius is proportional to the capacity of the SMRs on the site. C_{OPEX} and $C_{\mathrm{Emissions}}$ indicate the annual operating expenditure (OPEX) and emission cost. The emission cost is proportional to the carbon tax, which is provided as an input parameter. L and d are model parameters corresponding to the lifespan of the SMRs and discount rate, respectively.

The OPEX and emission cost for each sampled solution are determined by an Optimal Power Flow (OPF) analysis using the 29-bus model. The OPF calculates the optimal output from each generator, the voltage magnitude at each bus and the transmission loss across each branch in the network. This provides information to support the evaluation of each sampled solution in terms of the contribution of each generator to the power mix, the stability of the system and the efficiency of power transmission. The emissions from each generator were estimated using emissions intensities from Staffell [39].

The second step repeats the OPF analysis for five scenarios for the availability of wind (W) and solar (S) power: $\mathrm{W_H S_H}$, $\mathrm{W_H S_L}$, $\mathrm{W_M S_M}$, $\mathrm{W_L S_H}$, and $\mathrm{W_L S_L}$. The availabilities are categorised as high (H), medium (M), and low (L), and are determined by the maximum (H) and minimum (L) weekly average outputs, and average (M) annual outputs reported for wind and solar power by the Balancing Mechanism Reporting Service (BMRS) [19] via the National Grid: Live website [31] for 2022 (wind: 17 GW maximum weekly output, 2.89 GW minimum weekly output, 8.9 GW average annual output; solar: 2.9 GW maximum weekly output, 0.25 GW minimum weekly output, 1.4 GW average output). Each scenario is used to define an operational rate as a proportion of total capacity (wind: 23.6 GW, solar: 4.74 GW) that is applied uniformly to all wind and solar generators respectively.

The OPF analysis allowed the output of the SMRs to vary from 0 to 90% (the normal operating point for nuclear power generation [13]) of capacity. While it must be understood that is not feasible for real SMR operations, it is a deliberate feature of the analysis and is used to provide insights about the SMR capacity that is required in each location. The analysis allowed the output from generators fueled by coal, oil, and natural gas to vary from 0–90% (their normal operating point [13]) of capacity. This provides insight into the required output from each fossil-fueled generator as the carbon tax increases and SMRs are introduced. Low outputs (*i.e.*, close to 0%) indicate that a generator is no longer required (under that scenario), and that it could potentially be considered for decommissioning. The output of the wind and solar generators was allowed to vary up to the limit imposed by the scenario. However, the OPF analysis always returned solutions in which they operated at the prevailing upper bound. The output of conventional nuclear, hydro, and bioenergy generators was constrained in the ranges 0–70%, 0–25% and 35–50% of capacity respectively. Again, the OPF analysis always returned solutions at the upper bounds of these ranges, where the upper bounds were selected to match the average output observed in 2022 [19]. This treatment was necessary to facilitate the numerical convergence of the OPF solver.

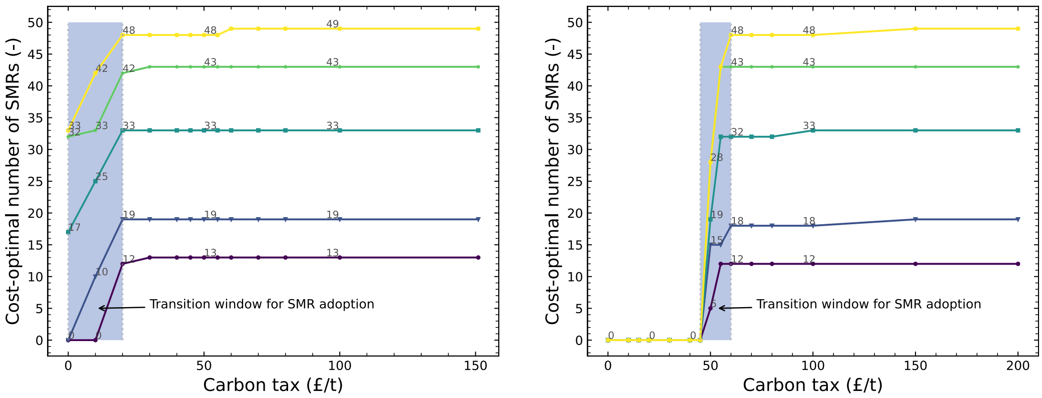
Full details of the model specification, model parameters, data sources and sites considered by the analysis are given in the Appendix. The analysis was implemented as part of The World Avatar (TWA) project, which uses a knowledge graph to provide a principled approach to integrating data from different sources [1]. The TWA is designed such that it would be straightforward to repeat the analysis elsewhere in the world.

3 Results

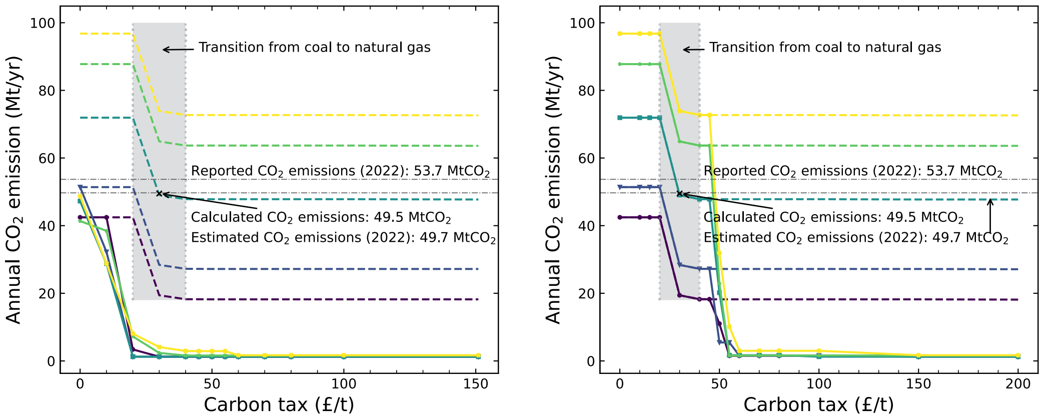
3.1 Cost-optimal number of SMRs, overall cost and emissions

Fig. 2 shows how the cost-optimal number of SMRs, and the corresponding emissions and cost vary as a function of the carbon tax for scenarios with SMRs that have an LCOE of £40/MWh and £60/MWh. The carbon tax penalises emissions, triggering the adoption of SMRs as the level of tax is increased.

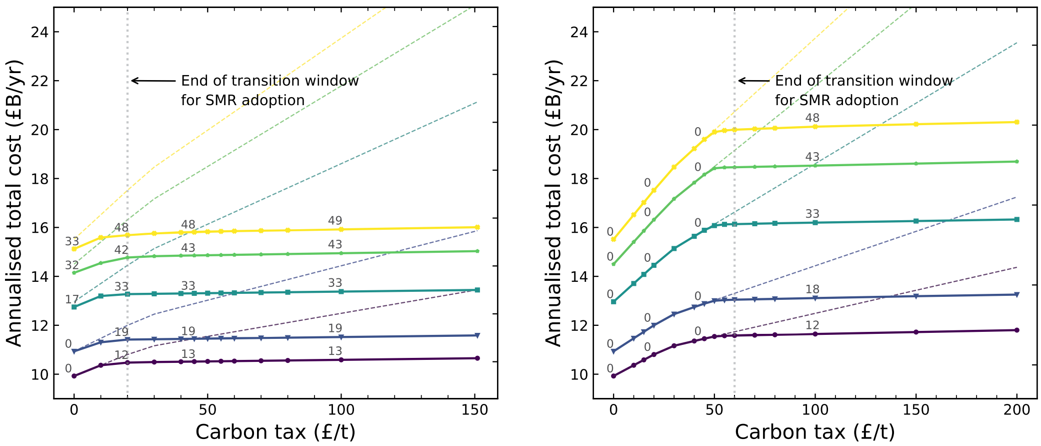
Fig. 2(a) shows a transition window (indicated by the blue shading) for SMR adoption for a carbon tax in the range £0–20/t for an LCOE of £40/MWh and £45–60/t for £60/MWh. Beyond the transition window, full adoption of SMRs is cost-effective. The final number of SMRs is sensitive to the assumptions about the availability of renewables in each scenario as should be expected, but *insensitive* to the cost of the SMRs. Conversely, the transition window is *insensitive* to the assumptions about the availability of renewables, but sensitive to the cost of the SMRs.



(a) Cost-optimal number of SMRs.



(b) Carbon emissions.



(c) Annualised cost. The data labels show the corresponding cost-optimal number of SMRs.

W_HS_H W_HS_L W_MS_M W_LS_H W_LS_L

Figure 2: *Cost-optimal number of SMRs, annualised cost and carbon emissions versus carbon tax for SMRs (weight = 0.5). Left: £40/MWh. Right: £60/MWh. Solid lines show scenarios corresponding to the operation of an electrical system with SMRs. Dashed lines show data for scenarios corresponding to the operation of the current electrical system without SMRs.*

The maximum cost-optimal number of SMRs varies between scenarios, ranging from 12–13 SMRs (5.6–6.1 GW), depending on the LCOE in the most renewable-abundant scenario (W_HS_H), to 49 SMRs (23 GW) in the least renewable-abundant scenario (W_LS_L). This highlights the significant impact of the assumptions about the availability of renewable energy on the required capacity of SMRs. It is noteworthy that the minimum cost-optimal number of SMRs is greater than zero at a carbon tax of £0/t for the combination of £40/MWh LCOE and low availability of renewables. Under these conditions, SMRs have lower operating costs than oil, coal and natural gas generators. Some scenarios show the introduction of an additional SMR beyond the transition window. This is due to the displacement of small residual amounts of fossil fuel from the power generation mix. The capacities involved are small relative to the capacity of an SMR, hence a high level of carbon tax is required before this becomes cost-effective.

Fig. 2(b) shows how the CO_2 emissions reduce as the number of SMRs increases. The emissions for each scenario reduce to almost zero across the transition window. There are some residual emissions beyond the transition window due to power generation from biomass and waste incineration, which the OPF analysis allows to persist as per the 2022 energy mix. The dashed lines show how the cost-optimal operation of the current energy system (without any SMRs and subject to the same assumptions about the availability of renewables) would respond to the carbon tax. The model predicts a transition window (indicated by the grey shading) where natural gas displaces coal and oil. Whether the SMR transition window occurs before or after this is sensitive to the cost of the SMRs. The switch to natural gas reduces emissions, but significant residual emissions remain after the transition in the absence of SMRs.

The model calculates emissions of 49.5 $MtCO_2$ from the current energy system in the W_MS_M scenario at a carbon tax of £30/t. This serves as a useful point of comparison because it corresponds to an energy mix that closely matches the average power mix in 2022 [31], so allows an assessment of the model against the real energy system. The 49.5 $MtCO_2$ estimated by the model is consistent with an estimate of 49.7 $MtCO_2$ calculated using the average power mix with the same emissions intensities as the model, and consistent with officially reported emissions of 53.7 $MtCO_2$ [36]. Full details of the emissions intensities and energy mix for this comparison are reported in the Appendix.

Fig. 2(c) shows that the cost increases as the number of SMRs increases, with corresponding differences between scenarios. As should be expected, the total cost is sensitive to the assumptions made with respect to the availability of renewables and the cost of the SMRs. The cost levels off beyond the transition window in the scenarios that introduce SMRs, corresponding to full adoption of SMRs and almost zero emissions. In contrast, the cost of scenarios that do not introduce SMRs (dashed lines) increases linearly with carbon tax because of the increasing penalty placed on emissions. After the onset of the transition window and under optimal power flow, a power system incorporating SMRs will be more cost-effective than a system based on the current generation mix, regardless of the level of carbon tax. Beyond the transition window, the level of carbon tax simply affects the level of incentive (*i.e.*, the difference in cost) to adopt SMRs. These findings highlight the potential economic benefits of adopting SMRs relative to the status quo, and emphasise the importance of considering carbon pricing mechanisms to encourage the transition towards low-carbon energy generation.

Fig. 3 shows the capacity of the current electrical power system in Great Britain (2022), overlaid by the average generation (2022) and capacity corresponding to different numbers of SMRs. The difference between average generation and overall capacity is indicative of the required reserve capacity. The SMRs correspond to a significant proportion of capacity and at the upper end, have a similar capacity to current coal, oil and natural gas generators. 52 SMRs would be sufficient to meet the current target of 24 GW nuclear capacity by 2050 [41], while 36 SMRs would be sufficient to provide 16.9 GW, which is the difference between the target and current conventional nuclear capacity.

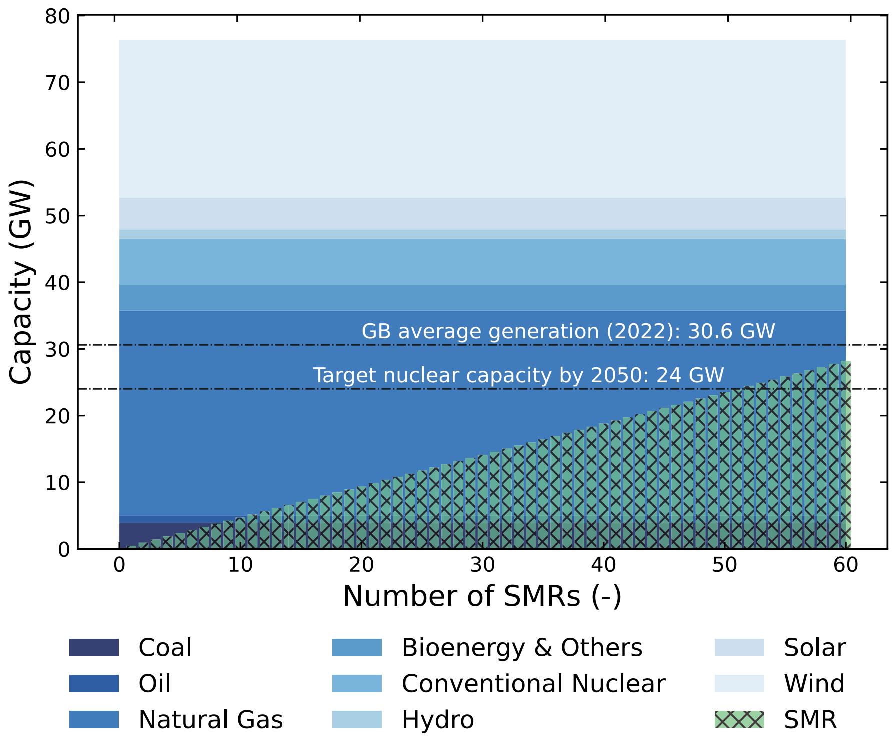


Figure 3: *Capacity of the electrical power system in Great Britain (2022) overlaid by the capacity corresponding to different numbers of SMRs. The dashed lines show the average demand in Great Britain (2022) [31] and the target for nuclear capacity in Great Britain by 2050 [41].*

3.2 Trade-offs in SMR placement

Fig. 4 shows that the competing objectives to place SMRs to minimise both site-demand distance and investment and risk cost form a Pareto front. The panel on the left shows the Pareto front formed by feasible solutions with 33 SMRs. The arrow labelled (A) shows a region of decrease in site-demand distance for relatively little increase in cost, while the arrow labelled (B) shows a region of increase in cost for little reduction in site-demand distance. The competing objectives are combined into a single objective. Low weights prioritise placement near centres of demand as a proxy to minimise transmission losses. High weights prioritise placement away from centres of population to minimise risk. The panel on the right shows the Pareto front for feasible designs with different numbers of SMRs. The figure is annotated with lines representing the UK target of 24 GW nuclear capacity by 2050, and the 16.9 GW difference between the target and current conventional nuclear capacity. The shaded area spans weights in the range 0.25–0.75. Designs in this region fall on the low-cost side of the apex of the Pareto front and balance both objectives. The designs corresponding to the points labelled (A), (B) and (C) are considered in more detail below.

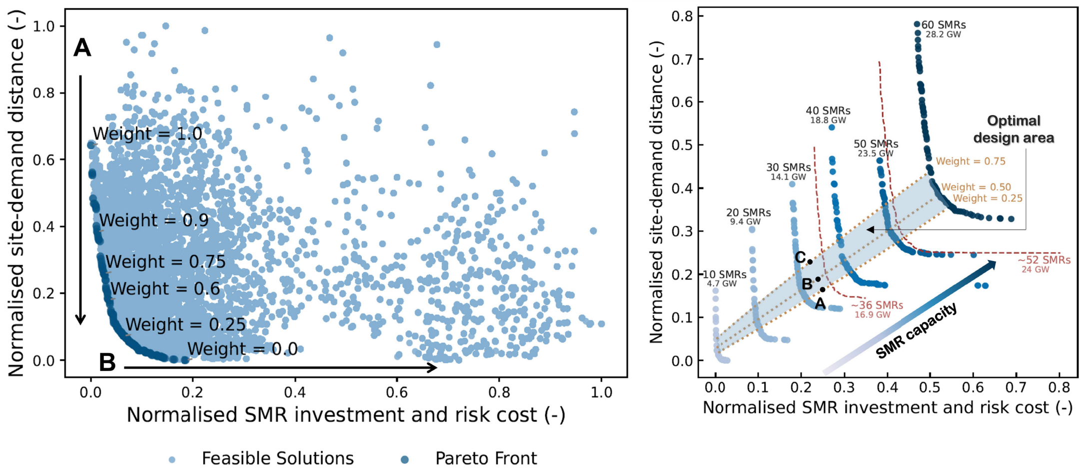
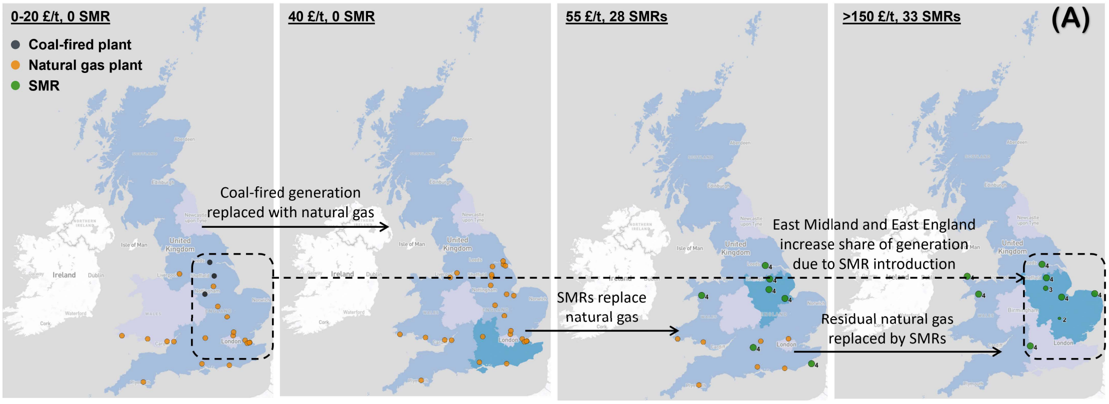


Figure 4: *Pareto front formed by competing objectives to minimise site-demand distance and investment and risk cost ($W_M S_M$ and LCOE of £60/MWh). Left: 33 SMRs. Right: 10–60 SMRs.*

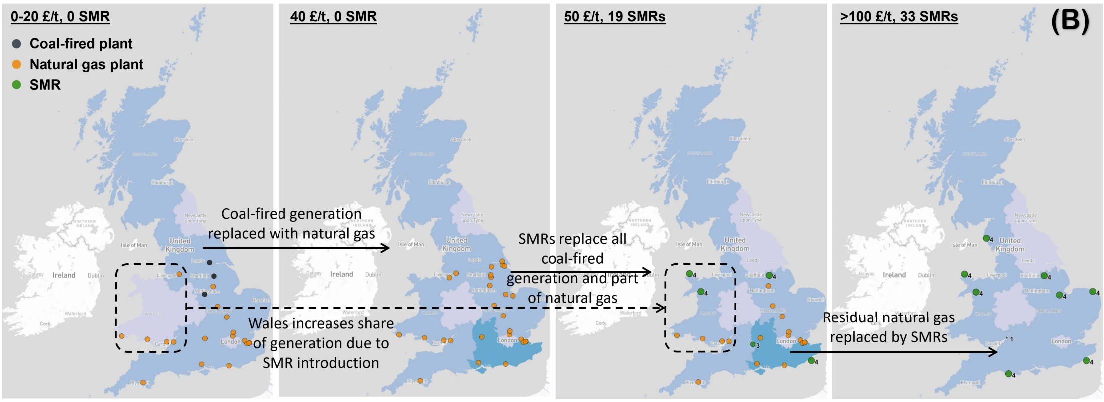
Fig. 5 shows the placement of SMRs for designs with different weights to control the placement policy for the $W_M S_M$ scenario and an LCOE of £60/MWh. Moving left to right, the figure shows how the designs change as the number of SMRs increases. The designs in the right-most column correspond to the points (A), (B) and (C) in Fig.4.

Fig. 5(a) shows designs where SMRs are placed near centres of demand to minimise transmission losses. The SMRs are mostly placed close to the East Midlands with some on the west coast of Wales, replacing the use of coal and eventually natural gas as the carbon tax is increased. Fig. 5(b) shows designs where SMRs are placed to balance proximity to centres of demand versus proximity to population. Fewer SMRs are now placed in the East Midlands, with more on the coast including the south and west coasts of England. Fig. 5(c) shows designs where SMRs are placed away from centres of population to minimise risk. SMRs are now also placed on the west coast of Scotland.

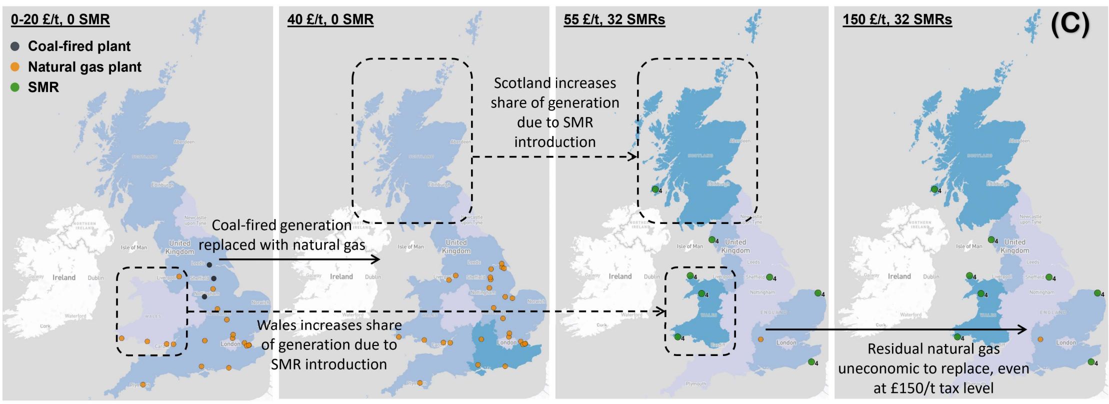
At extreme weights, the designs become problematic. As the weight approaches 1, the placement of SMRs that would optimally operate at low proportions of capacity becomes more prevalent, indicating that although the designs are feasible in terms of the SMR placement algorithm (Step 1 in Fig. 1), they are not acceptable in other respects. As the weight approaches 0, the designs become increasingly expensive as they move to more extreme points on the Pareto front, illustrated by the arrow labelled (B) on Fig. 4.



(a) SMRs are placed near centres of demand to minimise transmission losses (weight = 0.25).



(b) SMRs are placed to balance transmission losses versus proximity to population (weight = 0.50).



(c) SMRs are placed away from centres of population to minimise risk (weight = 0.75).

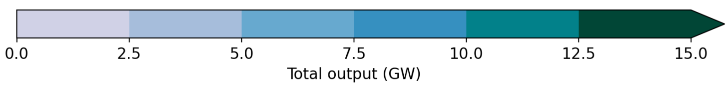


Figure 5: *Impact of placement policy on SMR locations ($W_M S_M$ and LCOE of £60/MWh).*

3.3 Impact of placement policy on energy independence

Fig. 6 shows the impact of the placement policy on transmission losses and net energy demand for the $W_M S_M$ scenario with 33 SMRs and an LCOE of £60/MWh. The panel on the left shows that low weights reduce transmission losses. The cost is reduced at intermediate weights, at the expense of increased transmission losses in Scotland and between Scotland and England. The reduction in cost arises from the reduction in risk cost as SMRs are placed away from centres of population. The panel on the right shows that high weights result in higher transmission losses and higher costs. A comparison of the three panels shows that the placement policy affects which regions are net importers or exporters of energy, with Scotland exporting more energy, and areas of England switching between being net importers and exporters as the weight increases. Results from the other scenarios are provided in the Appendix for comparison.

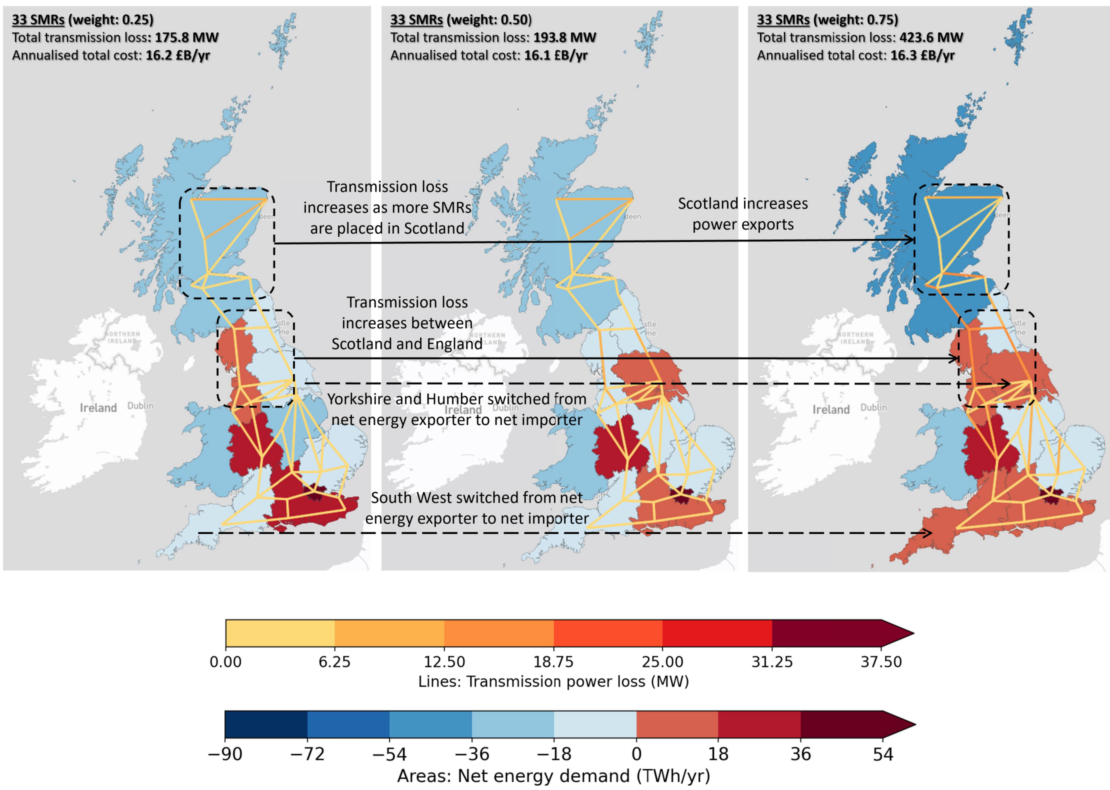


Figure 6: *Impact of placement policy on transmission loss and net demand ($W_M S_M$ and LCOE of £60/MWh).*

4 Conclusions

This work shows a carbon tax transition window above which the adoption of SMRs becomes cost-effective in place of power generation from oil, coal and gas. The value of the carbon tax in the transition window was insensitive to the assumptions made about the availability of renewable wind and solar power, but sensitive to the cost of the SMRs. A carbon tax in the range £45–60/t was observed to be required for SMRs with an LCOE of £60/MWh, versus £0–20/t for an LCOE of £40/MWh. Beyond the transition window, the SMR scenarios were always cheaper than scenarios based on the current generation mix.

Fig. 7 shows the sites and population density data [42] that were considered by the placement algorithm, together with the sites that were most commonly selected for the introduction of SMRs. The commonly selected sites fall into two broad groups: sites in the East Midlands that are close to centres of demand, and sites on the south and west coasts of Great Britain that are away from centres of population. They include Sellafield, Trawsfynydd and Wylfa, which were recommended by Rolls-Royce [20], but not Oldbury. These observations were insensitive to the assumptions made about the availability of renewable wind and solar power and the cost of the SMRs.

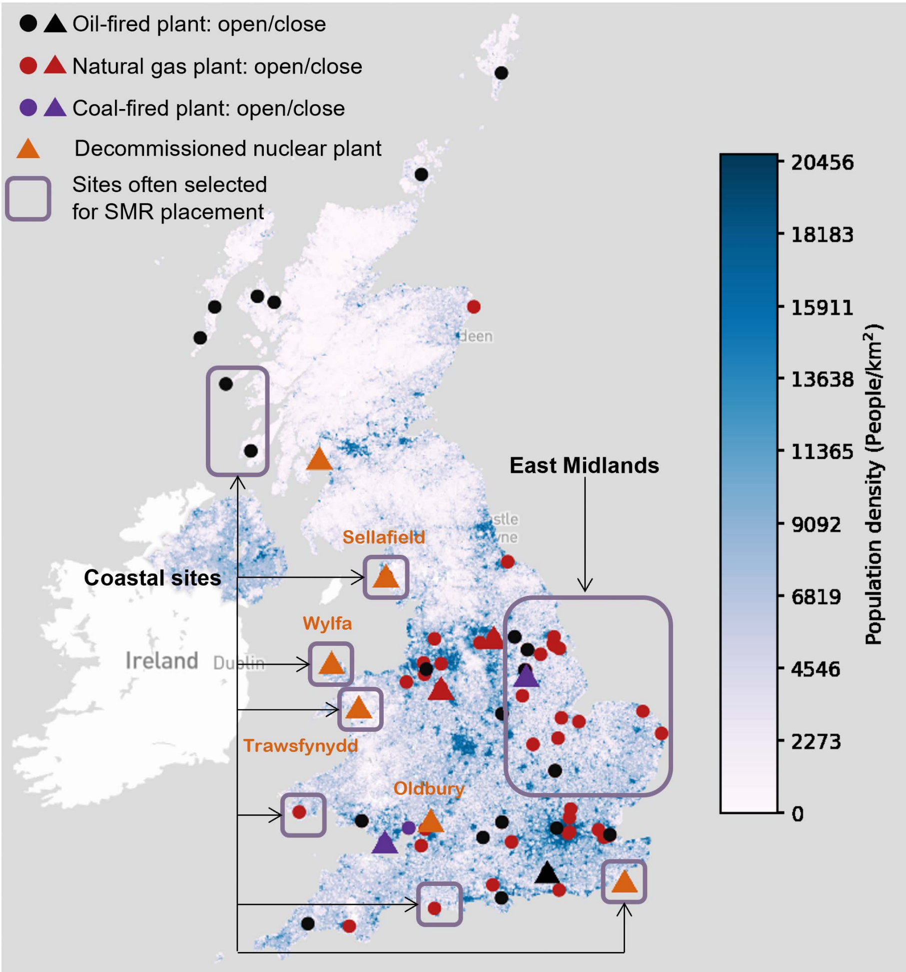


Figure 7: *Frequently selected sites for SMR placement ($W_M S_M$ and LCOE of £60/MWh) overlaid by population density.*

The optimal placement of the SMRs required a trade-off between minimising load-demand distance as a proxy for minimising transmission loss, and minimising population risk. The placement policy influenced the performance and cost of the resulting energy system, as well as whether a region acted as a net importer or exporter of energy. The most cost-effective solutions were achieved by balancing load-demand distance and population risk.

Declaration of generative AI and AI-assisted technologies in the writing process

The authors used ChatGPT version GPT-3.5 during the preparation of this work to enhance the readability and language of the manuscript. After using this tool, the authors reviewed and edited the content as needed and take full responsibility for the content of the publication.

Data and code availability

The codes developed for this work are available under an open-source licence on GitHub in The World Avatar repository https://github.com/cambridge-cares/TheWorldAvatar. The datasets used in the work are freely available for download as per the references in the paper. Archival copies of the datasets and instructions to reproduce the work are available in the University of Cambridge data repository (doi:10.17863/CAM.99921).

Acknowledgements

This research was supported by the National Research Foundation, Prime Minister's Office, Singapore under its Campus for Research Excellence and Technological Enterprise (CREATE) programme. Part of this work was also supported by Towards Turing 2.0 under the EPSRC Grant EP/W037211/1. The authors would further like to thank and acknowledge the financial support provided by the Cambridge Trust. Markus Kraft gratefully acknowledges the support of the Alexander von Humboldt Foundation. For the purpose of open access, the author has applied a Creative Commons Attribution (CC BY) licence to any Author Accepted Manuscript version arising.

A Appendix

A.1 Site placement problem specification

The number of SMRs to be installed at site s is calculated as

$$n_s = \sum_{i=0}^{N} i\, y_{s,i}, \tag{A.1}$$

where N is the maximum number of SMRs at a site and $y_{s,i}$ is a decision variable returned by the NSGA2 optimisation algorithm that denotes whether i SMRs are located on candidate site s. That is,

$$y_s \in \{0,1\}^{1+N} \quad \forall s, \tag{A.2}$$

subject to the constraint that

$$\sum_{i=0}^{N} y_{s,i} = 1 \quad \forall s. \tag{A.3}$$

The objectives used in Step 1 of the SMR placement algorithm are defined as

$$\Phi_1 = \sum_{s \in S_{\text{Candidate}}} C_{\text{CAPEX},s} + C_{\text{Risk},s}, \tag{A.4}$$

$$\Phi_2 = \sum_{s \in S_{\text{Candidate}}} \tilde{y}_s \left(\sum_{i \in D} L_{s,i}\, D_i \right), \tag{A.5}$$

where $S_{\text{Candidate}}$ denotes the set of candidate sites and D the set of demand areas,

$$C_{\text{CAPEX},s} = C_{\text{SMR}} \sum_{i=1}^{n_s} (1 - d_{\text{CAPEX}})^{i-1}, \tag{A.6}$$

$$C_{\text{Risk},s} = N\left(x_s,\ n_s \cdot r_{\text{SMR}} \cdot P_{\text{SMR}}\right)\ V\ P_{\text{Failure}}, \tag{A.7}$$

are the capital and risk cost associated with installing n_s SMRs at candidate site s. C_{SMR} is the unit cost of a single SMR and d_{CAPEX} is the discount rate for installing multiple SMRs on the same site. $N(x,r)$ is the population living within a radius r of location x, x_s is the location of candidate site s, r_{SMR} is the risk radius of an SMR per unit capacity, P_{SMR} is the unit capacity of a single SMR, V is the statistical value of a life, and P_{Failure} is the probability of an SMR experiencing an accident. $L_{s,i}$ is the distance between candidate site s and the centroid of demand area i, D_i is the demand of area i, and

$$\tilde{y}_s = \sum_{i=1}^{N} y_{s,i}, \tag{A.8}$$

is a derived decision variable. It takes the value 1 if any SMRs are placed on candidate site s and the value 0 otherwise.

The weighted objective used in Step 2 of the SMR placement algorithm is calculated as

$$\Phi = \frac{\hat{\Phi}_1}{1-w} + \frac{\hat{\Phi}_2}{w}, \quad w \in [\varepsilon, 1-\varepsilon], \tag{A.9}$$

where the hats $(\hat{\cdot})$ denote normalised quantities and w is a dimensionless weight that is clipped to avoid numerical overflow.

The annualised total cost used in Step 2 is calculated as

$$C_\text{T} = \frac{C_\text{CAPEX} + C_\text{Risk} + \sum_{l=1}^{L} \frac{C_\text{OPEX} + C_\text{Emissions}}{(1+d)^l}}{\frac{1-(1+d)^{-L}}{d}},$$

as per Eqn. (1) in the main text, where

$$C_\text{CAPEX} = \sum_{s \in S_\text{Candidate}} C_{\text{CAPEX},s}, \tag{A.10}$$

$$C_\text{Risk} = \sum_{s \in S_\text{Candidate}} C_{\text{Risk},s}. \tag{A.11}$$

The calculation assumes that the capital expenditure is incurred at the start of the project. This is conservative. In reality, the expenditure may be incurred over several years. For example, it is estimated that the construction of an SMR would take 4 years [44].

It is assumed that the annual costs are incurred at the end of each year, hence even the first term in the net present value sum in Eqn. (1) is discounted. The annual costs are calculated across all sites

$$C_\text{OPEX} = \sum_{s \in S_\text{All}} R_{f_s}\left(P_{\text{Capacity},s},\ P_{\text{Generated},s}\right) \cdot \Delta t, \tag{A.12}$$

$$C_\text{Emissions} = C_{\text{CO}_2} \left(\sum_{s \in S_\text{All}} e_{f_s} \cdot P_{\text{Generated},s} \cdot \Delta t \right), \tag{A.13}$$

where S_All denotes the set of all sites, C_{CO_2} is the rate of carbon tax, $P_{\text{Capacity},s}$ and $P_{\text{Generated},s}$ are the capacity of and the power generated by site s (calculated by the OPF analysis) respectively, Δt is the number of operational hours per year, f_s denotes the fuel type used at site s, e_f is the emission intensity and R_f is a polynomial cost function for fuel type f,

$$\begin{aligned} R_f\left(P_\text{Capacity},\ P_\text{Generated}\right) &= R_{0,f}\left(P_\text{Capacity}\right) + R_{1,f} \cdot P_\text{Generated}, \\ R_{0,f}\left(P_\text{Capacity}\right) &= \tilde{R}_{0,f} \cdot P_\text{Capacity}. \end{aligned} \tag{A.14}$$

The R_0 coefficient describes the fixed operational and maintenance costs. The R_1 coefficient describes the sum of variable production cost and fuel cost.

The type, location and capacity of generators [11] and the demand in each area of the country [17] were sourced from statistics published by the UK Government. The candidate sites for SMR placement were the subset of generator sites for existing fossil-fuel (68), former fossil-fuel (8) and former nuclear (6) power stations. The candidate sites are listed in Table A.1. The geometries of each demand area were sourced from the Office for National Statistics [35].

Table A.1: *Candidate sites for the placement of SMRs.*

Name	Type	Status	Latitude	Longitude
Coryton	CCGT	Open	51.51185	0.5079
Cottam Development Centre	CCGT	Open	53.30513	-0.78582
Damhead Creek	CCGT	Open	51.42491	0.6014
Didcot B	CCGT	Open	51.6246	-1.2683
Enfield	CCGT	Open	51.66248	-0.02247
Glanford Brigg	OCGT	Open	53.54109	-0.50556
Grain CHP	CCGT	Open	51.4444	0.7114
VPI Immingham	CCGT	Open	53.63682	-0.23772
Killingholme A	OCGT	Open	53.6592	-0.256
Killingholme B	OCGT	Open	53.65354	-0.2556
Langage	CCGT	Open	50.38821	-4.01175
Marchwood	CCGT	Open	50.8998	-1.4384
Medway	CCGT	Open	51.43956	0.68939
Pembroke	CCGT	Open	51.685	-4.99
Peterborough	OCGT	Open	52.5769	-0.204
Rocksavage	CCGT	Open	53.31472	-2.72323
Saltend	CCGT	Open	53.7348	-0.24341
Seabank	CCGT	Open	51.5392	-2.67
Severn Power	CCGT	Open	51.5475	-2.975
Shoreham	CCGT	Open	50.82925	-0.23109
South Humber Bank	CCGT	Open	53.60078	-0.14462
Staythorpe C	CCGT	Open	53.07296	-0.85852
Sutton Bridge	CCGT	Open	52.7579	0.1923
West Burton CCGT	CCGT	Open	53.36675	-0.7992
Peterhead	CCGT	Open	57.47797	-1.79046
Spalding	CCGT	Open	52.80685	-0.13546
Carrington	CCGT	Open	53.43653	-2.40956
Keadby_1	CCGT	Open	53.59468	-0.75149
Little Barford	CCGT	Open	52.20352	-0.27126
Rye_House	CCGT	Open	51.7616	0.00668
Baglan Bay	CCGT	Open	51.61409	-3.83818
Great Yarmouth	CCGT	Open	52.58407	1.73193
Corby	CCGT	Open	52.5108	-0.68348
Fellside CHP	CCGT	Open	54.4152	-3.49252
Wilton GT	Conventional steam	Open	54.5894	-1.1185
Blackburn	CCGT	Open	53.71812	-2.53922
Castleford	CCGT	Closed	53.7383	-1.39844
Sandbach	CCGT	Closed	53.16542	-2.40665
Thornhill	CCGT	Closed	53.67562	-1.6596

Name	**Type**	**Status**	**Latitude**	**Longitude**
Burghfield	OCGT	Open	51.3962	-1.09595
Chickerell	OCGT	Open	50.62358	-2.48977
Chippenham	OCGT	Open	51.34763	-2.74229
Pilkington Greengate	OCGT	Open	53.44219	-2.74238
London Heat Power	OCGT	Open	51.48565	-0.047
Barkantine Heat Power	OCGT	Open	51.49567	-0.02195
Aberthaw B	Coal	Closed	51.38731	-3.4049
Cottam	Coal	Closed	53.304	-0.7815
Uskmouth Power	Coal	Closed	51.54907	-2.97053
West Burton	Coal	Open	53.36046	-0.81019
Ratcliffe	Coal	Open	52.86463	-0.81019
Fiddlers Ferry	Coal	Closed	53.37234	-2.68912
Drax coal units	Coal	Open	53.74043	-0.9981
Cowes	Oil	Open	50.7469	-1.2862
Taylors Lane GT	Oil	Open	51.54598	-0.25844
Indian Queens	Oil	Open	50.39408	-4.75961
Didcot GT	Oil	Open	51.62455	-1.26865
Drax GT	Oil	Open	53.74043	-0.9981
Lerwick	Oil	Open	60.16696	-1.1669
Grain GT	Oil	Open	51.45297	0.71363
West Burton GT	Oil	Open	53.36243	-0.80904
Fiddlers Ferry GT	Oil	Open	53.37234	-2.68912
Ratcliffe GT	Oil	Open	52.86555	-1.25837
Baglan Bay GT	Oil	Open	51.61409	-3.83818
Keadby GT	Oil	Open	53.59468	-0.75149
Stornoway	Oil	Open	57.51699	-6.38222
Little Barford GT	Oil	Open	52.20661	-0.26903
Kirkwall	Oil	Open	58.98335	-2.9656
Loch Carnan South Uist	Oil	Open	57.36401	-7.27336
Arnish	Oil	Open	57.46102	-6.01822
Five Oaks 1	Oil	Closed	51.04471	-0.4439
Thatcham	Oil	Open	51.44866	-1.61429
Bowmore	Oil	Open	55.75695	-6.29093
Barra	Oil	Open	56.99862	-7.51996
Tiree	Oil	Open	56.49319	-6.90191
Connahs Quay	Sour gas	Open	53.22197	-3.06067
Knapton	Sour gas	Open	52.85101	1.40046
Wylfa	Nuclear	Closed	53.4159603	-4.4902244
Oldbury	Nuclear	Closed	51.6473724	-2.5721401
Sellafield	Nuclear	Closed	54.4205	-3.4975
Trawsfynydd	Nuclear	Closed	52.925567	-3.9507508
Dungeness B	Nuclear	Closed	50.9138436	0.9596944
Hunterston B	Nuclear	Closed	55.7214775	-4.8969607

The multi-objective optimisation problem was solved using the Non-dominated Sorting Genetic Algorithm (NSGA2) [9] from the ***pymoo*** Python package [5]. The optimisation is a Mixed Integer Linear Programming (MILP) problem, so Integer Random Sampling was chosen as the sampling method. The crossover method was Simulated Binary Crossover (SBX) [10], and the mutation operator was Polynomial Mutation (PM) [10]. The hyper-parameters for NSGA2 are given in Table A.2.

Table A.2: *NSGA2 hyperparameters.*

Hyperparameter	**Value**
Population size	500
Number of offspring	1000
Number of generations	600
Crossover probability	0.5
Crossover exchangeable tuning parameter	3.0
Mutation probability	1.0
Mutation exchangeable tuning parameter	3.0

The SMR specifications are based on the Rolls Royce prototype [43, 44]. The coefficients of the cost polynomials were sourced from the UK Government [16] for the year 2025. The emissions intensities were sourced from Staffell [39]. The parameter values are given in Tables A.3 and A.4.

Table A.4 additionally shows the actual fuel mix for power generation in the UK (averaged over 2022) [19, 31] and that predicted by the model ($W_M S_M$, no SMRs, carbon tax = £30/t) used for the comparison of actual versus modelled emissions as per Fig. 2(b) in the main text. The emissions for the model are calculated as per the term in brackets in Eqn. (A.13). The emissions for the actual fuel mix are calculated analogously

$$\sum_f e_f \cdot P_f \cdot \Delta t, \tag{A.15}$$

where f indexes the fuel type, e_f and P_f are the emissions intensity of and power produced from fuel type f and Δt is the number of operational hours per year as per Table A.3.

Table A.3: *Global model parameters.*

Parameter	**Value**	**Unit**	**Description**
Δt	8760	hours/year	Operational hours used to estimate annual energy production
C_{SMR}	1.8	£B (2021)	Cost of a single SMR [44]
d	3.5	%	Discount rate as per government LCOE calculations [13]
d_{CAPEX}	10	%	Discount rate for installing multiple SMRs on a site [18]
L	60	years	Lifespan of an SMR [44]
N	4	-	Maximum number of SMRs per site
P_{SMR}	470	MW	Capacity of a single SMR [44]
P_{Failure}	0.002985	-	Probability of an SMR experiencing an accident [18]
r_{SMR}	200	m/MW	Risk radius of an SMR per unit capacity [18]
V	2.4	£M/person	Statistical value of a human life [18]

Table A.4: *Fuel-specific model parameters: Coefficients of cost polynomials (2025) [16], emission intensities [39] and UK fuel mix for power generation (2022).*

Fuel type	$\tilde{R}_0$ (£/MWh)	R_1 (£/MWh)	**Emission intensity (gCO_2/kWh)**	**Generation (Actual) (GW)**	**Generation (Model) (GW)**
Coal	12	28	937	0.49	0
Oil	21	63	935	-	0
Natural gas (OCGT)	21	63	651	12.72	0
Natural gas (CCGT)	2	43	394		13.85
Biomass	43	52	120	1.71	1.64
Conventional nuclear	11	10	0	5.10	5.03
SMRs	15.5, 35.5†	5	0	-	0
Solar	10	0	0	1.40	1.39
Wind onshore	10	6	0	8.82	4.75
Wind offshore	19	3	0		4.24
Hydro	15	6	0	0.38	0.44
Pumped hydro	17	42	0	-	0
Other	21	63	0.15	-	0
Total generation (GW)				30.6	31.3
Emissions ($MtCO_2$/year)				49.7‡	49.5

† These values correspond to an LCOE of £40/MWh and £60/MWh respectively. See Table A.5.
‡ The calculation assumes that all natural gas is used via CCGTs. An alternative estimate using the reported overall emissions intensity of 182 gCO_2/kWh (2022) [31], a total power generation of 30.6 GW (from the table) and an operating period of 8760 hours/year gives 48.8 $MtCO_2$/year, which remains consistent.

Table A.5 shows a breakdown of the contributions to the LCOE for SMRs for a £40/MWh and £60/MWh case. The total LCOEs match the values published for the Roll-Royce prototype [43, 44]. The cost types and calculation method follow the standard LCOE methodology developed by Mott MacDonald [32] for the UK Government [13]. The capital (pre-development and construction) contributions are calculated by discounting the cost of an SMR as per the standard methodology [32]

$$\frac{C_{\text{SMR}}}{\sum_{l}^{L} \frac{\phi \cdot P_{\text{SMR}} \cdot \Delta t}{(1+d)^{l}}} = 19.5 \text{ £/MWh}, \tag{A.16}$$

where $\phi = 90\%$ is the assumed long-term operating point of the SMR and C_{SMR}, P_{SMR}, Δt, L and d are defined as per Table A.3.

The fuel cost contribution is assumed to be the same as for conventional nuclear [13]. The remaining cost is apportioned to operation and maintenance (O&M) and is assumed to incorporate a component to account for decommissioning and waste. This is consistent with the assumption made by Mott MacDonald [32] when developing the LCOE methodology.

There is insufficient information to rigorously disaggregate the fixed and variable O&M costs. The analysis in this paper assumes that the O&M costs in Table A.5 contribute to the fixed as opposed to variable part (*i.e.*, to the $\tilde{R}_0$ as opposed to R_1 term) of the cost function for the SMRs. This is conservative in the sense that it results in a larger contribution to the overall operating cost, but may not be significant. This can be seen in Eqn. A.14, where by definition $P_{\text{Generated}} \leq P_{\text{Capacity}}$, and where the OPF analysis returns that $P_{\text{Generated}} \approx 0.9 P_{\text{Capacity}}$, except where specifically noted otherwise in the main text.

Table A.5: *SMR LCOE cost breakdown.*

Cost type	**Contribution to LCOE**	
	(£/MWh)	**(£/MWh)**
Pre-development Construction	19.5	19.5
Fixed O&M Variable O&M	15.5	35.5
Fuel	5	5
Total LCOE	40	60

A.2 29-bus model specification

Fig. A.1 shows the locations of the generators, buses and branches in the 29-bus model of the UK high-voltage power transmission system. The model includes 29 buses, 99 branches and 1129 generators The generators were clustered to the nearest bus based on the shortest Euclidian distance; the demand from each area of the country was clustered to the nearest bus based on the shortest Euclidian distance from the centroid of the demand area. The type, location and capacity of the generators [11], and the demand in each area of the country [17] were sourced from statistics published by the UK Government. The geometries of each demand area were sourced from the Office for National Statistics [35]. The buses and branches were specified as per Belivanis [4] as per Tables A.6–A.8.

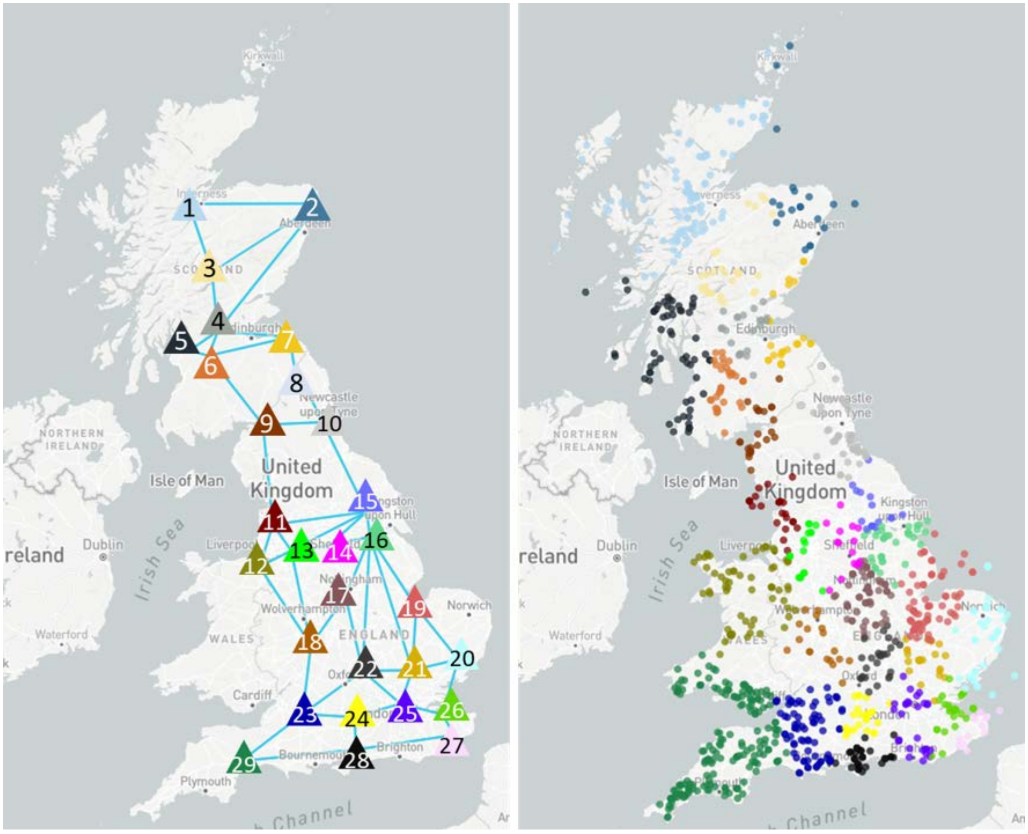


Figure A.1: *29-bus model of the UK high-voltage power transmission system. Left: Buses and connecting branches. Right: Generators, colour-coded by bus.*

The Optimal Power Flow (OPF) analysis was solved using the ***pypower*** Python package [27] with the base power specified as 100 MVA. Full descriptions of the parameters in Tables A.7 and A.8 are given in the MATPOWER user manual [46]. Brief descriptions are given below for completeness.

Bus specification

- **Type** specifies the type of bus. 1: PQ bus, 2: PV bus and 3: slack bus.
- **Pd** and **Qd** are real and reactive power demand.
- **Gs** and **Bs** are the shunt conductance and susceptance.
- **VM** and **Va** are the voltage magnitude and angle.
- **BasekV** is the base voltage.
- **Vmax** and **Vmin** are the maximum and minimum voltage magnitudes.
- **Area** specifies which parts of the OPF should be solved simultaneously. The default setting is used such that the whole problem is solved simultaneously.
- **Zone** refers to a range of operating conditions or system states where the objective is to minimize power losses. The default setting is used.

Branch specification

- **Resistance**, **Reactance** and total line charging **Susceptance** of each branch.
- **Rate A**, **Rate B** and **Rate C** denote the long-term, short-term and emergency rating of each branch, respectively.
- **Ratio** is a transformer TAP ratio. A value of 0 or 1 indicate that a branch is a pure transmission line.
- **Angle** specifies the transformer phase shift angle.
- **Status** identifies the initial branch status with a value of 1 for in-service and 0 for out-of-service.
- **Angmin** and **Angmin** represent the minimum and maximum angle difference allowed for the branch.

Table A.6: *Bus specification for the 29-bus model (part 1).*

Bus	Name	Latitude	Longitude
1	Beauly	57.4698798	-4.4906735
2	Peterhead	57.4745293	-1.7998211
3	Errochty	56.7070037	-4.0107947
4	Denny/Bonnybridge	56.0386335	-3.8890767
5	Neilston	55.8095298	-4.4768292
6	Strathaven	55.7509421	-4.0805189
7	Torness	55.966361	-2.4082467
8	Eccles	55.6684972	-2.3299805
9	Harker	54.9419311	-2.9618091
10	Stella West	54.9744212	-1.7329921
11	Penwortham	53.7443568	-2.7549931
12	Deeside	53.2292472	-3.0317476
13	Daines	53.4269672	-2.3787821
14	Th. Marsh/Stocksbridge	53.4877894	-1.6016288
15	Thornton/Drax/Eggborough	53.9002325	-0.8235841
16	Keadby	53.5973069	-0.755805
17	Ratcliffe	52.862919	-1.257635
18	Feckenham	52.2512438	-1.9735155
19	Walpole	52.7269277	0.1981251
20	Bramford	52.0716528	1.0631638
21	Pelham	51.9351319	0.1167908
22	Sundon/East Claydon	51.9270632	-0.9099366
23	Melksham	51.3749726	-2.1441581
24	Bramley	51.3358918	-1.0775578
25	London	51.5077431	-0.1271547
26	Kemsley	51.3684603	0.7414151
27	Sellindge	51.1050295	0.9761146
28	Lovedean	50.9163709	-1.0383188
29	South West Penisula	50.7674626	-3.4061633

Table A.7: *Bus specification for the 29-bus model (part 2).*

Bus	**Type** (-)	**Pd** (MW)	**Gd** (MVAr)	**Gs** (MW)	**Bs** (MVAr)	**Vm** (p.u.)	**Va** (°)	**basekV** (kV)	**Vmax** (p.u.)	**Vmin** (p.u.)	**Area** (-)	**Zone** (-)
1	2	253.77	0	0	0	1	0	275	1.1	0.9	1	1
2	2	307.22	0	0	0	1	0	275	1.1	0.9	1	1
3	2	143.73	0	0	0	1	0	132	1.1	0.9	1	1
4	2	511.18	0	0	0	1	0	275	1.1	0.9	1	1
5	2	714.06	0	0	0	1	0	400	1.1	0.9	1	1
6	2	330.88	0	0	0	1	0	400	1.1	0.9	1	1
7	2	338.81	0	0	0	1	0	400	1.1	0.9	1	1
8	1	229.72	0	0	0	1	0	400	1.1	0.9	1	1
9	1	258.63	0	0	0	1	0	400	1.1	0.9	1	1
10	2	1137.06	0	0	0	1	0	400	1.1	0.9	1	1
11	2	940.91	0	0	0	1	0	400	1.1	0.9	1	1
12	2	1176.79	0	0	0	1	0	400	1.1	0.9	1	1
13	1	1973.83	0	0	0	1	0	400	1.1	0.9	1	1
14	1	1756.77	0	0	0	1	0	400	1.1	0.9	1	1
15	2	373.9	0	0	0	1	0	400	1.1	0.9	1	1
16	2	917.01	0	0	0	1	0	400	1.1	0.9	1	1
17	2	1641.36	0	0	0	1	0	400	1.1	0.9	1	1
18	2	2471.87	0	0	0	1	0	400	1.1	0.9	1	1
19	2	789.18	0	0	0	1	0	400	1.1	0.9	1	1
20	2	707.34	0	0	0	1	0	400	1.1	0.9	1	1
21	2	617.87	0	0	0	1	0	400	1.1	0.9	1	1
22	2	1159.02	0	0	0	1	0	400	1.1	0.9	1	1
23	2	1693.36	0	0	0	1	0	400	1.1	0.9	1	1
24	1	1062.12	0	0	0	1	0	400	1.1	0.9	1	1
25	2	5364.87	0	0	0	1	0	400	1.1	0.9	1	1
26	2	852.58	0	0	0	1	0	400	1.1	0.9	1	1
27	3	495.96	0	0	0	1	0	400	1.1	0.9	1	1
28	2	1300.1	0	0	0	1	0	400	1.1	0.9	1	1
29	2	1739.41	0	0	0	1	0	400	1.1	0.9	1	1

Table A.8: *Branch specification for the 29-bus model.*

From/To bus		R (p.u.)	B (p.u.)	X (p.u.)	RateA (MVA)	RateB (MVA)	RateC (MVA)	Ratio (-)	Angle (°)	Status (-)	Angmin (°)	Angmax (°)
1	2	0.0122	0.02	0.0856	525	525	525	0	0	1	-360	360
1	3	0.007	0.15	0.052	132	132	132	1	2	1	-360	360
1	2	0.0122	0.02	0.2844	525	525	525	0	0	1	-360	360
1	3	0.007	0.15	0.052	132	132	132	1	2	1	-360	360
2	4	0.0004	0.065	0.4454	760	760	760	0	0	1	-360	360
2	4	0.0004	0.065	0.5545	760	760	760	0	0	1	-360	360
4	7	0.00211	0.0135	0.1174	1090	1090	1090	0	0	1	-360	360
4	6	0.0013	0.023	0.1496	1500	1500	1500	0	0	1	-360	360
4	6	0.0013	0.023	0.1758	1120	1120	1120	0	0	1	-360	360
4	5	0.001	0.024	0.125	1000	1000	1000	0	0	1	-360	360
4	5	0.001	0.024	0.125	1000	1000	1000	0	0	1	-360	360
4	7	0.0021	0.0135	0.1538	1090	1090	1090	0	0	1	-360	360
5	6	0.00085	0.01051	0.38254	1390	1390	1390	0	0	1	-360	360
5	6	0.00151	0.01613	0.59296	1390	1390	1390	0	0	1	-360	360
6	9	0.00078	0.00852	0.0737	2100	2100	2100	0	0	1	-360	360
6	9	0.00078	0.00852	0.4635	2100	2100	2100	0	0	1	-360	360
7	8	0.0004	0.0001	0.728	2180	2180	2180	0	0	1	-360	360
7	8	0.0004	0.0001	1.2872	2500	2500	2500	0	0	1	-360	360
7	6	0.003	0.2	0.2939	950	950	950	0	0	1	-360	360
7	6	0.003	0.2	0.2939	950	950	950	0	0	1	-360	360
8	10	0.00083	0.0175	0.6624	3070	3070	3070	0	0	1	-360	360
8	10	0.00083	0.0175	0.6624	3070	3070	3070	0	0	1	-360	360
9	11	0.00164	0.0163	0.4868	1390	1390	1390	0	0	1	-360	360
9	11	0.00164	0.0163	0.4868	1390	1390	1390	0	0	1	-360	360
9	10	0.00352	0.02453	0.1898	855	855	855	0	0	1	-360	360
9	10	0.00492	0.0343	0.2502	775	775	775	0	0	1	-360	360
10	15	0.00053	0.00835	5.373	4840	4840	4840	0	0	1	-360	360
10	15	0.00052	0.0063	1.0636	4020	4020	4020	0	0	1	-360	360
11	15	0.0007	0.042	0.3907	2520	2520	2520	0	0	1	-360	360
11	15	0.00099	0.042	0.5738	2520	2520	2520	0	0	1	-360	360
11	13	0.0004	0.0052	0.2498	2170	2170	2170	0	0	1	-360	360
11	13	0.0004	0.0052	0.2664	2210	2210	2210	0	0	1	-360	360
11	12	0.0001	0.0085	0.0798	3320	3320	3320	0	0	1	-360	360
11	12	0.0001	0.0085	0.0798	3320	3320	3320	0	0	1	-360	360
12	13	0.00096	0.01078	0.385	3100	3100	3100	0	0	1	-360	360
12	18	0.00074	0.009	0.2911	2400	2400	2400	1	2	1	-360	360
12	18	0.00097	0.009	0.3835	2400	2400	2400	0	0	1	-360	360
12	13	0.00096	0.01078	0.385	3100	3100	3100	1	2	1	-360	360
13	18	0.00049	0.007	0.1943	2400	2400	2400	0	0	1	-360	360
13	18	0.00084	0.007	0.7759	2400	2400	2400	0	0	1	-360	360
13	15	0.00137	0.023	0.6643	1240	1240	1240	0	0	1	-360	360
13	15	0.00164	0.023	0.1104	955	955	955	0	0	1	-360	360
13	14	0.00107	0.01163	1.1745	1040	1040	1040	0	0	1	-360	360
13	14	0.00082	0.01201	1.2125	1040	1040	1040	0	0	1	-360	360
14	16	0.0005	0.016	0.2795	2580	2580	2580	0	0	1	-360	360
14	16	0.005	0.018	0.1466	625	625	625	0	0	1	-360	360
15	16	0.00033	0.0052	0.3534	2770	2770	2770	0	0	1	-360	360
15	16	0.00016	0.00172	0.3992	5540	5540	5540	0	0	1	-360	360
15	14	0.00019	0.00222	0.7592	5000	5000	5000	0	0	1	-360	360

From/To bus		R (p.u.)	B (p.u.)	X (p.u.)	RateA (MVA)	RateB (MVA)	RateC (MVA)	Ratio (-)	Angle (°)	Status (-)	Angmin (°)	Angmax (°)
15	14	0.00018	0.00222	0.5573	5000	5000	5000	0	0	1	-360	360
16	19	0.00056	0.0141	0.4496	2780	2780	2780	0	0	1	-360	360
16	19	0.00056	0.0141	0.4496	3820	3820	3820	0	0	1	-360	360
17	16	0.001	0.01072	0.2651	2150	2150	2150	0	0	1	-360	360
17	16	0.001	0.01072	0.4573	1890	1890	1890	0	0	1	-360	360
17	22	0.00068	0.0097	0.4566	2100	2100	2100	0	0	1	-360	360
17	22	0.00069	0.0097	0.4574	2100	2100	2100	0	0	1	-360	360
18	17	0.00042	0.0018	0.2349	3100	3100	3100	0	0	1	-360	360
18	17	0.00042	0.0018	0.2349	3460	3460	3460	0	0	1	-360	360
18	23	0.00138	0.0096	0.4829	1970	1970	1970	0	0	1	-360	360
18	23	0.00117	0.0096	0.4122	1970	1970	1970	0	0	1	-360	360
20	26	0.00035	0.0023	0.2249	2780	2780	2780	0	0	1	-360	360
20	26	0.00035	0.0023	0.2249	2780	2780	2780	0	0	1	-360	360
20	19	0.00178	0.0213	0.6682	1590	1590	1590	0	0	1	-360	360
20	19	0.00132	0.0143	0.3656	1590	1590	1590	0	0	1	-360	360
21	16	0.00145	0.01824	0.9169	2780	2780	2780	0	0	1	-360	360
21	16	0.00145	0.01824	0.9169	2780	2780	2780	0	0	1	-360	360
21	25	0.00025	0.01	0.1586	2780	2780	2780	0	0	1	-360	360
21	25	0.00025	0.01	0.1586	2780	2780	2780	0	0	1	-360	360
21	20	0.0012	0.0048	0.4446	2780	2780	2780	0	0	1	-360	360
21	20	0.0012	0.0048	0.7	2780	2780	2780	0	0	1	-360	360
21	19	0.00037	0.0059	0.294	3030	3030	3030	0	0	1	-360	360
21	19	0.00037	0.0059	0.2955	2780	2780	2780	0	0	1	-360	360
22	16	0.00178	0.0172	0.8403	2010	2010	2010	0	0	1	-360	360
22	16	0.00178	0.0172	0.627	2010	2010	2010	0	0	1	-360	360
22	25	0.00037	0.0041	0.4098	3275	3275	3275	0	0	1	-360	360
22	25	0.00034	0.0041	0.429	3275	3275	3275	0	0	1	-360	360
22	21	0.00019	0.00111	0.1232	2780	2780	2780	0	0	1	-360	360
22	21	0.00048	0.0061	0.3041	2780	2780	2780	0	0	1	-360	360
23	29	0.00151	0.0182	0.53	2010	2010	2010	0	0	1	-360	360
23	24	0.00086	0.0008	0.9622	2780	2780	2780	0	0	1	-360	360
23	24	0.00023	0.0007	2.8447	4400	4400	4400	0	0	1	-360	360
23	22	0.00055	0.003	0.3468	2780	2780	2780	0	0	1	-360	360
23	22	0.00039	0.003	0.2466	2770	2770	2770	0	0	1	-360	360
23	29	0.00151	0.0182	0.53	2010	2010	2010	0	0	1	-360	360
24	28	0.00068	0.007	0.2388	2210	2210	2210	0	0	1	-360	360
24	25	0.00104	0.0091	0.2918	1390	1390	1390	0	0	1	-360	360
24	25	0.00104	0.0091	0.2918	1390	1390	1390	0	0	1	-360	360
24	28	0.00068	0.007	0.2388	2210	2210	2210	0	0	1	-360	360
25	26	0.0002	0.0057	0.532	6960	6960	6960	0	0	1	-360	360
25	26	0.0002	0.0057	0.532	5540	5540	5540	0	0	1	-360	360
27	26	0.0002	0.00503	0.1797	3100	3100	3100	0	0	1	-360	360
27	26	0.0002	0.00503	0.1797	3100	3100	3100	0	0	1	-360	360
28	27	0.00038	0.00711	0.2998	3070	3070	3070	0	0	1	-360	360
28	27	0.00038	0.00711	0.2998	3070	3070	3070	0	0	1	-360	360
29	28	0.00051	0.00796	0.34	2780	2780	2780	0	0	1	-360	360
29	28	0.00051	0.00796	0.34	2780	2780	2780	0	0	1	-360	360
3	4	0.003	0.041	0.0044	648	648	648	0	0	1	-360	360
3	4	0.003	0.041	0.044	648	648	648	0	0	1	-360	360
3	2	0.03004	0.077	0.0124	652	652	652	0	0	1	-360	360

A.3 Additional figures

Figures A.2–A.5 show the impact of placement policy on SMR locations and transmission losses for scenarios that are not shown in the main text. Each figure shows the maximum number of SMRs for the corresponding scenario.

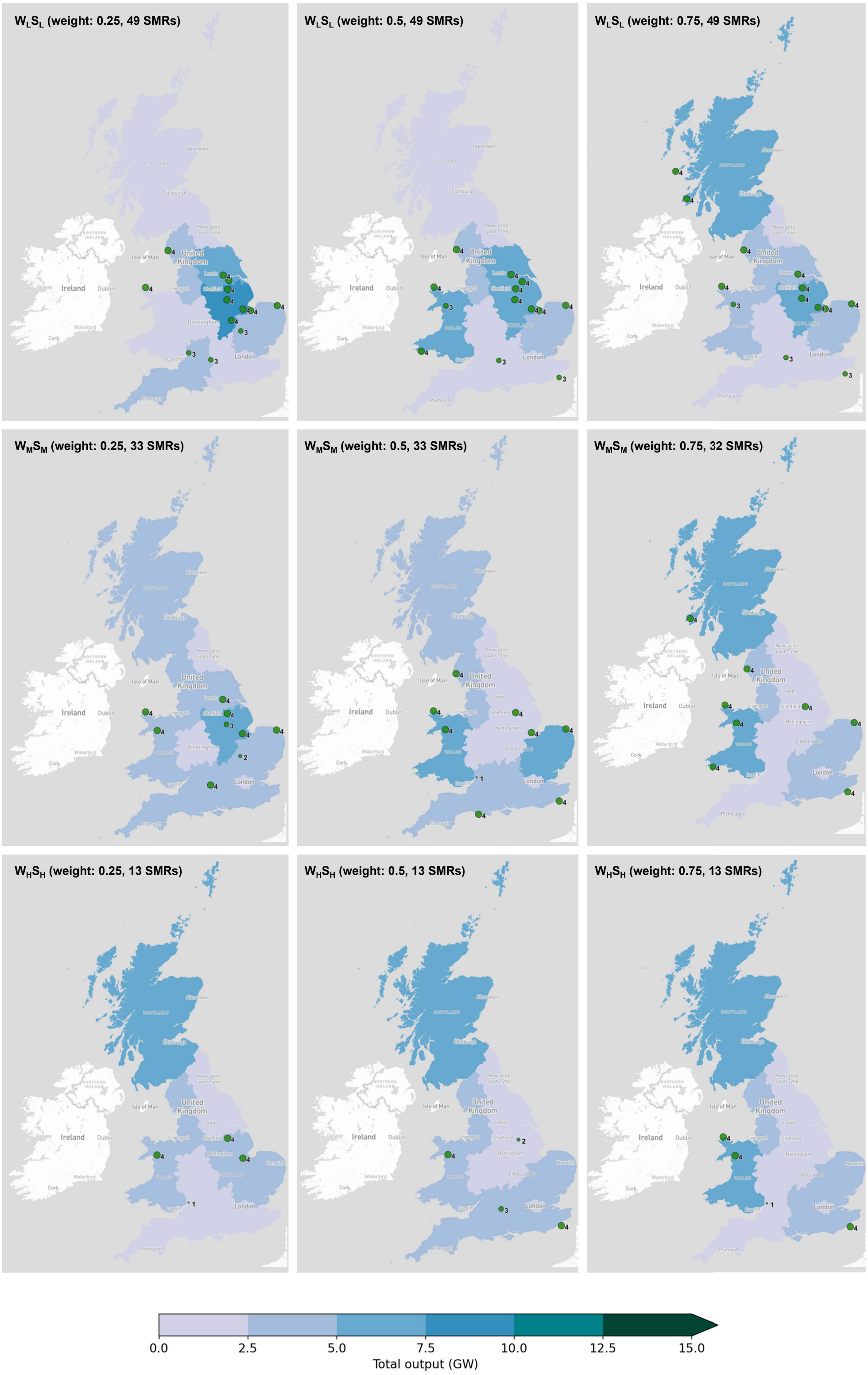


Figure A.2: *Impact of placement policy on SMR locations, LCOE = £40/WMh. Left to right: weight = 0.25, 0.5, 0.75. Top to bottom:* W_LS_L, W_MS_M, W_HS_H.

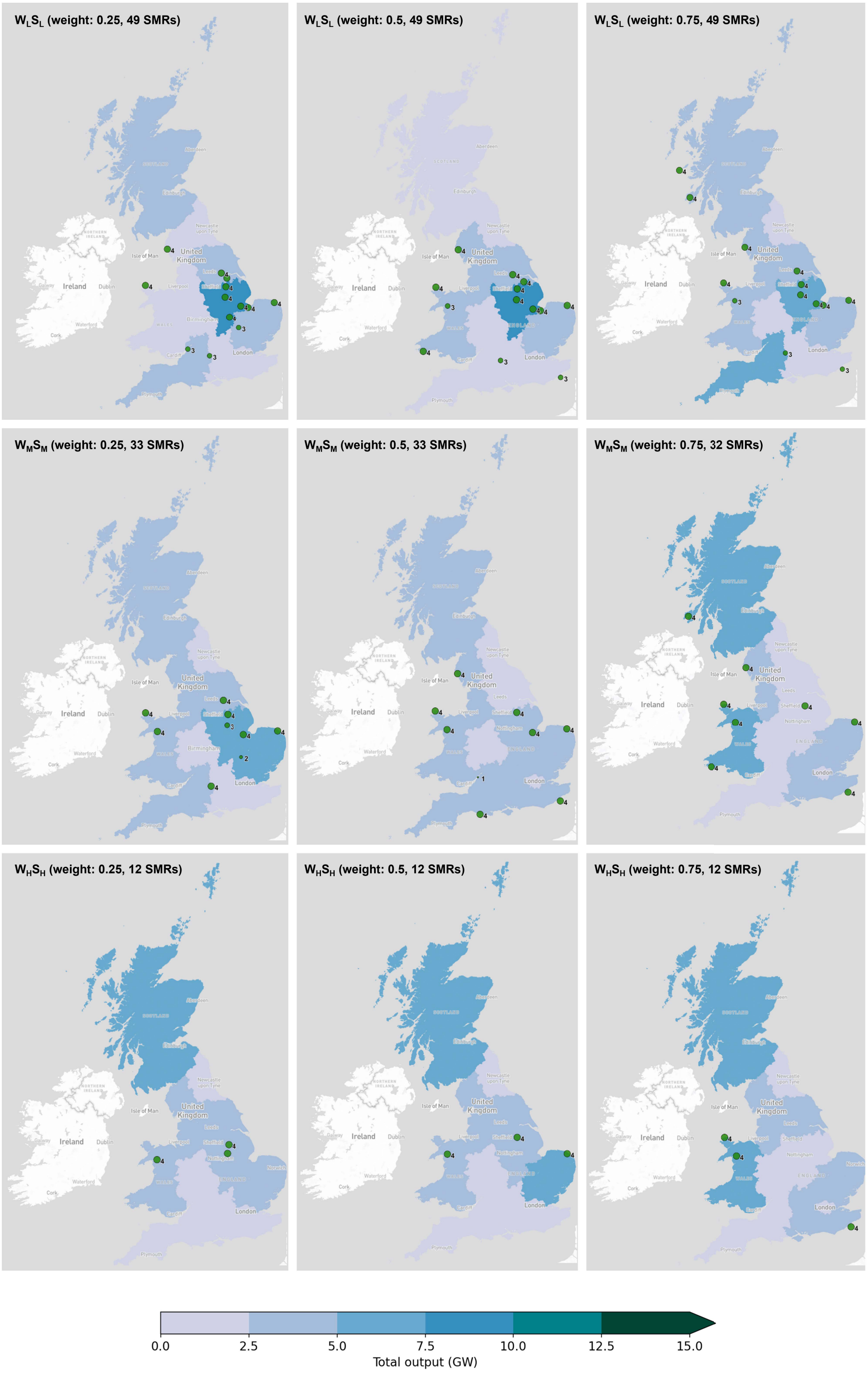


Figure A.3: *Impact of placement policy on SMR locations, LCOE = £60/WMh. Left to right: weight = 0.25, 0.5, 0.75. Top to bottom:* $W_L S_L$, $W_M S_M$, $W_H S_H$.

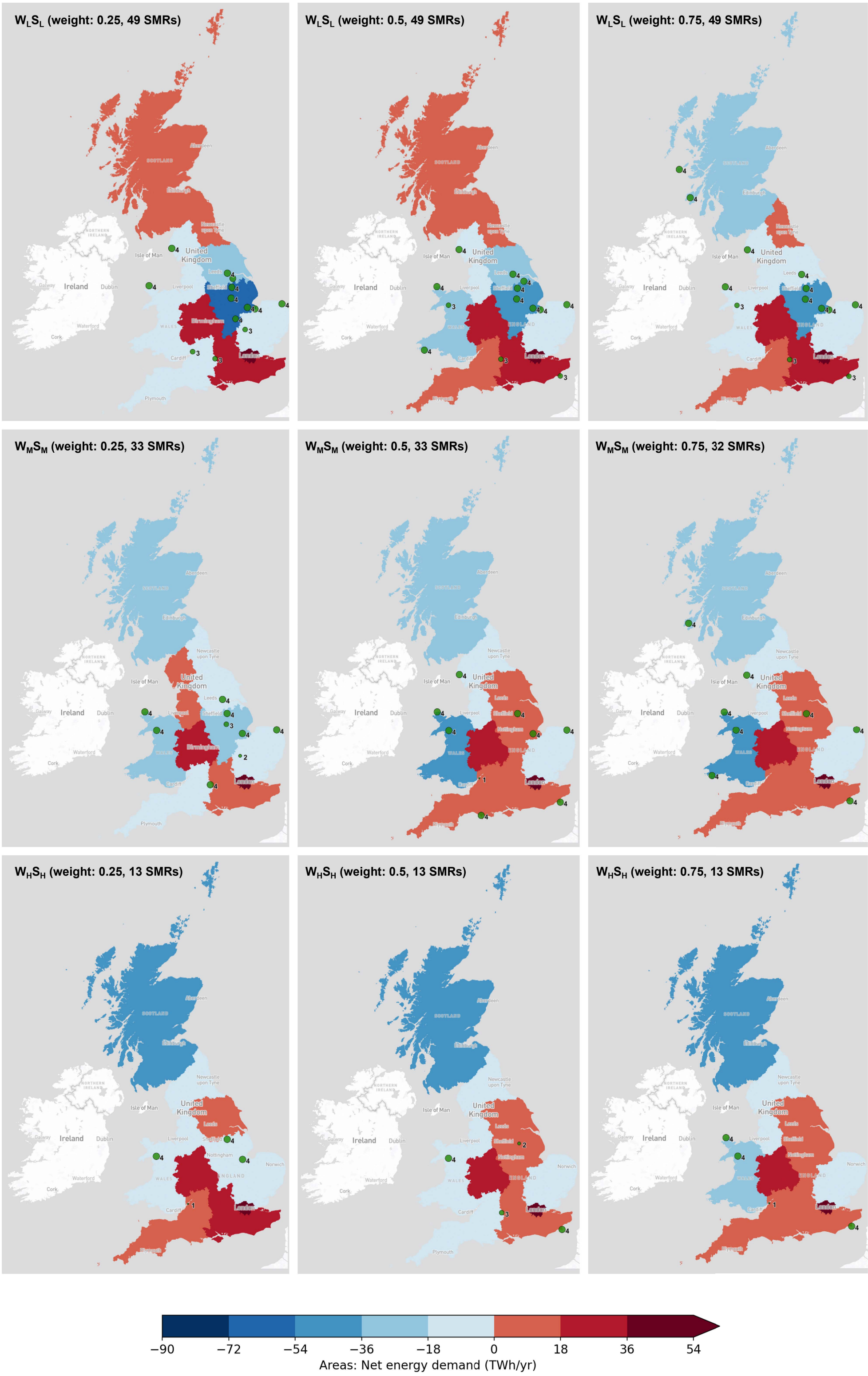


Figure A.4: *Impact of placement policy on transmission loss and net demand, LCOE = £40/WMh. Left to right: weight = 0.25, 0.5, 0.75. Top to bottom:* $W_L S_L$, $W_M S_M$, $W_H S_H$.

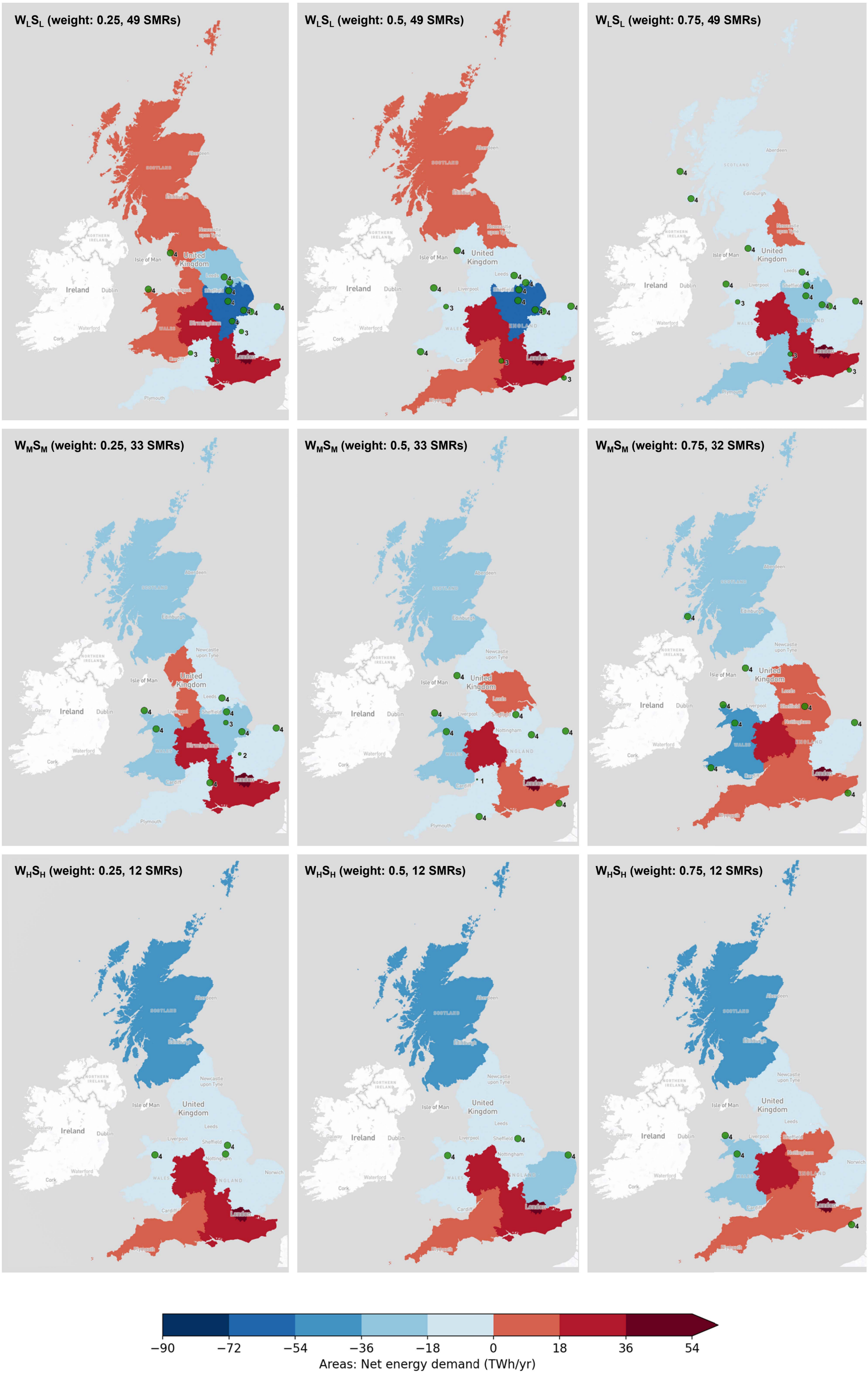


Figure A.5: *Impact of placement policy on transmission loss and net demand, LCOE = £60/WMh. Left to right: weight = 0.25, 0.5, 0.75. Top to bottom: W_LS_L, W_MS_M, W_HS_H.*

Nomenclature

AMR Advanced Modular Reactor

ASEAN Association of South East Asian Nations

BMRS Balancing Mechanism Reporting Service

CAPEX Capital expenditure

CCGT Combined Cycle Gas Turbine

CCS Carbon Capture and Storage

CPF Carbon Price Floor

ETS Emissions Trading System

LCOE Levelised Cost of Electricity

NSGA2 Non-dominated Sorting Genetic Algorithm II

OCGT Open Cycle Gas Turbine

OPF Optimal Power Flow

SMR Small Modular Reactor

$\mathbf{W_H S_H}$ High wind and high solar power availability

$\mathbf{W_H S_L}$ High wind and low solar power availability

$\mathbf{W_L S_H}$ Low wind and high solar power availability

$\mathbf{W_L S_L}$ Low wind and low solar power availability

$\mathbf{W_M S_M}$ Mid-level wind and mid-level solar power availability

References

[1] J. Akroyd, S. Mosbach, A. Bhave, and M. Kraft. Universal Digital Twin – A Dynamic Knowledge Graph. *Data-Centric Engineering*, 2:e14, 2021. doi:10.1017/dce.2021.10.

[2] A. Asuega, B. J. Limb, and J. C. Quinn. Techno-economic analysis of advanced small modular nuclear reactors. *Applied Energy*, 334:120669, 2023. doi:10.1016/j.apenergy.2023.120669.

[3] J. Atherton, W. Xie, L. K. Aditya, X. Zhou, G. Karmakar, J. Akroyd, S. Mosbach, M. Q. Lim, and M. Kraft. How does a carbon tax affect Britain's power generation composition? *Applied Energy*, 298:117117, 2021. doi:10.1016/j.apenergy.2021.117117.

[4] M. Belivanis. Power Systems Test Case Archive, 2013. URL https://www.maths.ed.ac.uk/optenergy/NetworkData/reducedGB. Accessed Feb 2023.

[5] J. Blank and K. Deb. pymoo: Multi-objective optimization in python. *IEEE Access*, 8:89497–89509, 2020. doi:10.1109/ACCESS.2020.2990567.

[6] Business and the environment. GDA Step 1 of the Rolls-Royce SMR: statement of findings, 2023. URL https://www.gov.uk/government/publications/gda-step-1-of-the-rolls-royce-smr-statement-of-findings/gda-step-1-of-the-rolls-royce-smr-statement-of-findings. Accessed Feb 2023.

[7] B. Cárdenas, R. Ibanez, J. Rouse, L. Swinfen-Styles, and S. Garvey. The effect of a nuclear baseload in a zero-carbon electricity system: An analysis for the UK. *Renewable Energy*, 205:256–272, 2023. doi:10.1016/j.renene.2023.01.028.

[8] Climate Change Committee. Progress in reducing emissions 2022 Report to Parliament, 2022. URL https://www.theccc.org.uk/publication/2022-progress-report-to-parliament/. Accessed Feb 2023.

[9] K. Deb, A. Pratap, S. Agarwal, and T. Meyarivan. A fast and elitist multiobjective genetic algorithm: NSGA-II. *IEEE Transactions on Evolutionary Computation*, 6 (2):182–197, 2002. doi:10.1109/4235.996017.

[10] K. Deb, K. Sindhya, and T. Okabe. Self-adaptive simulated binary crossover for real-parameter optimization. In *Proceedings of the 9th annual conference on Genetic and evolutionary computation*, 2007. doi:10.1145/1276958.1277190.

[11] Department for Business, Energy & Industrial Strategy. Power stations in the United Kingdom, May 2022 (DUKES 5.11), 2022. URL https://www.gov.uk/government/statistics/electricity-chapter-5-digest-of-united-kingdom-energy-statistics-dukes. Accessed Feb 2023.

[12] Department for Energy Security and Net Zero. The ten point plan for a green industrial revolution, 2020. URL https://www.gov.uk/government/publications/the-ten-point-plan-for-a-green-industrial-revolution. Accessed April 2023.

[13] Department for Energy Security and Net Zero and Department for Business, Energy & Industrial Strategy. BEIS electricity generation cost report (November 2016). Technical report, Department for Energy Security and Net Zero and Department for Business, Energy & Industrial Strategy, 2016. URL https://www.gov.uk/government/publications/beis-electricity-generation-costs-november-2016. Accessed Feb 2023.

[14] Department for Energy Security and Net Zero and Department for Business, Energy & Industrial Strategy. Small Modular Reactors: Techno-Economic Assessment. Technical report, Department for Energy Security and Net Zero and Department for Business, Energy & Industrial Strategy, 2016. URL https://www.gov.uk/government/publications/small-modular-reactors-techno-economic-assessment. Accessed April 2023.

[15] Department for Energy Security and Net Zero and Department for Business, Energy & Industrial Strategy. Nuclear energy in the UK (2019), 2019. URL https://www.gov.uk/government/publications/energy-trends-march-2019-special-feature-article-nuclear-electricity-in-the-uk. Accessed Feb 2023.

[16] Department for Energy Security and Net Zero and Department for Business, Energy & Industrial Strategy. BEIS Electricity Generation Costs (2020). Technical report, Department for Energy Security and Net Zero and Department for Business, Energy & Industrial Strategy, 2020. URL https://www.gov.uk/government/publications/beis-electricity-generation-costs-2020. Accessed Feb 2023.

[17] Department for Energy Security and Net Zero and Department for Business, Energy & Industrial Strategy. Sub-national gas consumption data, 2021. URL https://www.gov.uk/government/collections/sub-national-gas-consumption-data. Accessed Feb 2023.

[18] A. Devanand, M. Kraft, and I. A. Karimi. Optimal site selection for modular nuclear power plants. *Computers & Chemical Engineering*, 125:339–350, 2019. doi:10.1016/j.compchemeng.2019.03.024.

[19] Elexon. Balancing Mechanism Reporting Service, 2023. URL https://www.bmreports.com/bmrs. Accessed Feb 2023.

[20] Environment Agency, Office for Nuclear Regulation, and Natural Resources Wales. Small Modular Reactor design completes first step of assessment, 2023. URL https://www.gov.uk/government/news/small-modular-reactor-design-completes-first-step-of-assessment. Accessed Feb 2023.

[21] European Court of Auditors. Energy taxation, carbon pricing and energy subsidies, 2022. URL https://www.eca.europa.eu/Lists/ECADocuments/RW22_01/RW_Energy_taxation_EN.pdf. Accessed Feb 2023.

[22] S. Gao, G. Huang, X. Zhang, J. Chen, and D. Han. SMR siting for the electricity system management. *Journal of Cleaner Production*, 297:126621, 2021. doi:10.1016/j.jclepro.2021.126621.

[23] S. Gao, G. Huang, X. Zhang, and D. Han. Small modular reactors enable the transition to a low-carbon power system across canada. *Renewable and Sustainable Energy Reviews*, 169:112905, 2022. doi:10.1016/j.rser.2022.112905.

[24] K. Gugler, A. Haxhimusa, and M. Liebensteiner. Effectiveness of climate policies: Carbon pricing vs. subsidizing renewables. *Journal of Environmental Economics and Management*, 106:102405, 2021. doi:10.1016/j.jeem.2020.102405.

[25] E. Haves. Nuclear power in the UK (2021), 2021. URL https://lordslibrary.parliament.uk/nuclear-power-in-the-uk/. Accessed Feb 2023.

[26] D. Hirst. Carbon Price Floor (CPF) and the price support mechanism, 2018. URL https://commonslibrary.parliament.uk/research-briefings/sn05927. Accessed June 2023.

[27] R. Lincoln. Pypower 5.1.16, 2023. URL https://pypi.org/project/PYPOWER/. Accessed Feb 2023.

[28] Y. Liu, G. Huang, J. Chen, X. Zhang, X. Zheng, and M. Zhai. Development of an optimization-aided small modular reactor siting model – a case study of saskatchewan, canada. *Applied Energy*, 305:117867, 2022. doi:10.1016/j.apenergy.2021.117867.

[29] C. Matthew and A. Walker. Nuclear energy in the UK (2022), 2022. URL https://post.parliament.uk/research-briefings/post-pn-0687. Accessed Feb 2023.

[30] J.-L. Mo and L. Zhu. Using floor price mechanisms to promote carbon capture and storage (ccs) investment and CO_2 abatement. *Energy & Environment*, 25(3-4):687–707, 2014. doi:10.1260/0958-305x.25.3-4.687.

[31] K. R. Morley. National Grid: Live, 2023. URL https://grid.iamkate.com/. Accessed Feb 2023.

[32] Mott MacDonald. UK Electricity Generation Costs Update. Technical report, Department of Energy & Climate Change, 2010. URL https://www.gov.uk/government/publications/uk-electricity-generation-costs-mott-macdonald-update-2010. Accessed Feb 2023.

[33] National Grid ESO. Carbon Intensity API, 2023. URL https://carbonintensity.org.uk/. Accessed June 2023.

[34] V. Nian, B. Mignacca, and G. Locatelli. Policies toward net-zero: Benchmarking the economic competitiveness of nuclear against wind and solar energy. *Applied Energy*, 320:119275, 2022. doi:10.1016/j.apenergy.2022.119275.

[35] Office for National Statistics. ONS Statistical Geography Ontology, 2023. URL https://statistics.data.gov.uk/def/statistical-geography. Accessed Feb 2023.

[36] C. O'Sullivan. 2022 UK greenhouse gas emissions, provisional figures. Technical report, Department for Energy Security and Net Zero, 2023. URL https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/1147372/2022_Provisional_emissions_statistics_report.pdf. Accessed Feb 2023.

[37] Sean Bray. Carbon Taxes in Europe, 2022. URL https://taxfoundation.org/carbon-taxes-in-europe-2022/. Accessed June 2023.

[38] Secretary of State for Business, Energy and Industrial Strategy. Energy white paper: Powering our net zero future, 2020. URL https://www.gov.uk/government/publications/energy-white-paper-powering-our-net-zero-future. Accessed Feb 2023.

[39] I. Staffell. Measuring the progress and impacts of decarbonising British electricity. *Energy Policy*, 102:463–475, 2017. doi:10.1016/j.enpol.2016.12.037.

[40] B. Steigerwald, J. Weibezahn, M. Slowik, and C. von Hirschhausen. Uncertainties in estimating production costs of future nuclear technologies: A model-based analysis of small modular reactors. *Energy*, page 128204, 2023. doi:10.1016/j.energy.2023.128204.

[41] UK Government. British energy security strategy, 2022. URL https://www.gov.uk/government/publications/british-energy-security-strategy/british-energy-security-strategy#nuclear. Accessed April 2023.

[42] United Nations Office for the Coordination of Humanitarian Affairs (OCHA). United Kingdom: High Resolution Population Density Maps + Demographic Estimates, 2020. URL https://www.maths.ed.ac.uk/optenergy/NetworkData/reducedGB/. Accessed Feb 2023.

[43] World Nuclear News. UK confirms funding for Rolls-Royce SMR, 2019. URL https://www.world-nuclear-news.org/Articles/UK-confirms-funding-for-Rolls-Royce-SMR. Accessed Feb 2023.

[44] World Nuclear News. Rolls-Royce on track for 2030 delivery of UK SMR, 2021. URL https://world-nuclear-news.org/Articles/Rolls-Royce-on-track-for-2030-delivery-of-UK-SMR. Accessed Feb 2023.

[45] X. Zhang, G. Huang, X. Zhou, L. Liu, and Y. Fan. A multicriteria small modular reactor site selection model under long-term variations of climatic conditions – a case study for the province of saskatchewan, canada. *Journal of Cleaner Production*, 290:125651, 2021. doi:10.1016/j.jclepro.2020.125651.

[46] R. D. Zimmerman and C. E. Murillo-Sánchez. Matpower user's manual, 2020.