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A comprehensive assessment of the energy performance of the full range of electricity generation technologies deployed in the United Kingdom

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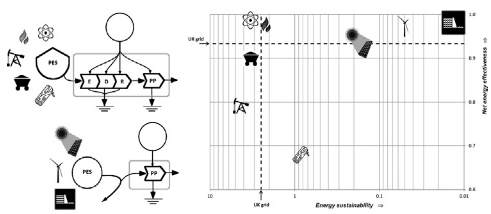
HIGHLIGHTS

- We assess the energy performance of electricity generation technologies in the UK.
- The NEA and LCA methodologies are reviewed and discussed.
- *Net energy gain* and *non-renewable cumulative energy demand* are deemed key metrics.
- Wind, and to a lesser extent PV, are found to be the most recommendable technologies.
- Natural gas combined cycles are also recognised as important for dispatchability.

GRAPHICAL ABSTRACT



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ABSTRACT

We performed a comprehensive and internally consistent assessment of the energy performance of the full range of electricity production technologies in the United Kingdom, integrating the viewpoints offered by net energy analysis (NEA) and life cycle assessment (LCA). Specifically, the energy return on investment (EROI), net-to-gross energy output ratio (NTG) and non-renewable cumulative energy demand (nr-CED) indicators were calculated for coal, oil, gas, biomass, nuclear, hydro, wind and PV electricity. Results point to wind, and to a lesser extent PV, as the most recommendable technologies overall in order to foster a transition towards an improved electricity grid mix in the UK, from both points of view of short-term effectiveness at providing a net energy gain to support the multiple societal energy consumption patterns, and long-term energy sustainability (the latter being inversely proportional to the reliance on non-renewable primary energy sources). The importance to maintain a sufficient installed capacity of readily-dispatchable gas-fired electricity is also recognised.

1. Introduction

1.1. The key role of electricity and the challenges ahead

Exponential population growth and the progressive industrialisation of many developing countries have led to steadily increasing energy use, and projections indicate that global demand for primary energy is likely to grow by an additional 37% by

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2040 (International Energy Agency (IEA), 2014a). Also, over the course of the last century, and increasingly so in recent decades, industrialised societies have become more and more reliant on electricity as a versatile and 'clean' (at the point of use) energy carrier (EC), and this trend is projected to accelerate even further in the foreseeable future (International Energy Agency (IEA), 2014a).

Worldwide, electricity is still largely driven (~70% of total generation) by thermal technologies feeding on non-renewable primary energy sources (PES)-namely coal, oil and natural gas-whose largest extant deposits are geographically localised, and whose combustion results in the emission of large quantities of greenhouse gases (GHGs). Critical dependence upon fossil fuels for electricity generation is therefore cause for concern in terms of both national energy security (for many non-producing countries) and global climate change. The remaining share of global electricity output is dominated by hydroelectric (~15%) and nuclear (~10%) – both low-carbon technologies, but of which the latter still relies on a non-renewable PES. All other low-carbon technologies that harvest renewable primary energy, including biomass, wind, geothermal, solar and tidal, still collectively only supply ~5% of global electricity demand (International Energy Agency (IEA), 2014b).

Given this state of matters, major technological and political challenges lie ahead if increasingly industrialised societies are to continue to meet the growing demand for electricity, while at the same time reducing their dependency on finite stocks of non-renewable PES, and attempting to contain global warming (e.g., at least within a proposed +2 °C threshold (United Nations Framework Convention on Climate Change (UNFCCC), 2009)-and even achieving this may in fact not be enough to prevent major disruptions to the world's ecosystems (Lenton, 2011; Knopf et al., 2012)).

Addressing these challenges will require a multi-pronged approach that takes into account a whole gamut of constraints, ranging from economic affordability to technical feasibility and environmental sustainability. Notable issues to take into account are the levelized cost of electricity (Ouyang and Lin, 2014; Boccard, 2014; Klein and Whalley, 2015; del Río and Cerdá, 2014; Maxim, 2014; Pickard, 2012), the feasibility of large-scale energy storage, blending of different generation technologies into a functional grid mix, and demand-side management (Gross et al., 2006; Nikolakakis and Fthenakis, 2011; Denholm and Hand, 2011; Grünewald et al., 2012; Römer et al., 2012; Nyamdash and Denny, 2013; Solomon et al., 2014; Brennan, 2010; Levine and Sonnenblick, 1994; Barton et al., 2013; Strbac, 2008; Garg et al., 2011; Bergaentzlé et al., 2014; Martínez Ceseña et al., 2015), and the impending climate constraints and the technological measures devised to address them in the short, medium and long terms (Lilliestam et al., 2012; Martinsen et al., 2007; Lai et al., 2012; Scott, 2013; Levi and Pollitt, 2015).

Mindful of all this, we hereby present a balanced and internally consistent assessment of the actual *energy performance* of the range of currently available electricity production pathways in the UK, *intended as a key pre-requisite* to the consideration of all the issues mentioned above, and aimed at providing preliminary policy recommendations on which technologies appear to be best suited to enable a transition to a more sustainable electricity mix for the future – again from an *energy* point of view.

1.2. Electricity production mix in the UK

The UK's electricity generation mix in 2013-the most recent year for which official data were available-was not dissimilar from that of the world as a whole, in terms of the overall preponderance of non-renewable PES (~85% of total), albeit with a higher penetration of nuclear (19% of total), as illustrated in Table 1.

Table 1
Electricity production technologies comprising the UK electric grid mix and relative shares of total electricity output in the year 2013 (Department of Energy & Climate Change (DECC), 2014a; National Grid, 2014a).

Technology	Share of total grid output (%)
Coal	37.0
Oil	0.6
Gas	1.3
Gas combined cycle	26.7
Nuclear	19.1
Biomass	4.8
Hydro	1.4
Wind (on shore)	4.0
Wind (off-shore)	4.4
PV	0.7

Concerns over this state of matters has led the system operator for the national electricity transmission system in the UK to draft a number of stakeholder-informed scenarios for the future evolution of the grid mix over the next 20 years. The scenarios differ in their assumptions about the availability of economic resources and stability of political commitment to low-carbon options, and lead to a range of possible grid mixes in the year 2035, as illustrated in Table 2.

These scenarios will provide the backdrop to the discussion of the policy implications of our own results in Section 5.

1.3. Net Energy Analysis (NEA)

One defining characteristic of an energy supply chain-regardless of whether it primarily feeds on a renewable or non-renewable PES, and irrespective of the final EC that it is designed to deliver (e.g., thermal energy contained in a fuel, or electricity)-is that it must provide the end user with a positive *energy surplus* (also referred to as *net energy gain* or NEG). The latter may be calculated starting with the amount of primary energy harvested from the PES, and subtracting all the energy dissipated to the environment along the supply chain (i.e., all processing, transformation and delivery steps required to turn the 'raw' primary energy into a usable EC at the point of use), as well as all the additional energy that has to be 'invested' in order to carry out the same chain of processes. If this condition is not met, then a system may still of course play a useful societal role (e.g. by contributing to matching supply and demand for a specific type of EC), but it no

Table 2
Electricity output by production technology in 2013 and projected changes in the year 2035, according to four alternative scenarios developed by National Grid (2014a).

Technology	TWh_{el} (2013)	TWh_{el} (2035) "No Progression"	TWh_{el} (2035) "Slow Progression"	TWh_{el} (2035) "Gone Green"	TWh_{el} (2035) "Low Carbon Life"
Coal	124	3	3	4	4
Coal CCS	0	0	3	30	32
Oil	2	0	0	0	0
Gas	94	159	53	55	53
Gas CCS	0	0	7	30	49
Nuclear	64	31	50	68	93
Biomass	16	17	17	25	20
Hydro	5	7	10	17	16
Wind (off-shore+off-shore)	28	64	132	170	106
PV	3	7	10	17	16