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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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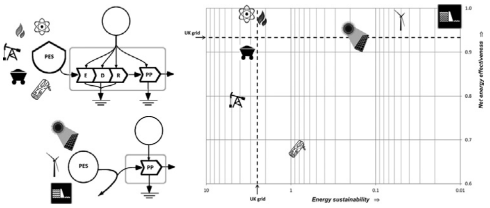
HIGHLIGHTS

- 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

longer behaves as an overall net supplier of energy, and becomes an energy consumer instead.

This is the basic premise of the discipline known as Net Energy Analysis (NEA), which leads to the ranking of alternative energy supply chains according to a range of related indicators, all of which hinge on this very concept of NEG (Slesser, 1974; Leach, 1975; Chambers et al., 1979; Herendeen, 1988; Cleveland et al., 1984; Cleveland, 1992; Herendeen, 2004; Carbajales-Dale et al., 2014).

Futhermore, from the NEA perspective a merely positive NEG is a necessary, but not sufficient, condition for an energy supply chain to be considered recommendable. This is because the energy sector as a whole must in fact support not only itself (for which a NEG just over zero would suffice), but in fact all other non-energy producing sectors of society as well. In other words, this points to the importance of maintaining a *sufficiently* large NEG from the energy supply sector as a whole, in order to ensure the continued support of the complex exosomatic metabolism of a modern society (Hall et al., 2009; Lambert et al., 2014).

The adjective “exosomatic” refers to “energy converted outside the human body, but still converted into applied power under human control, in order to facilitate the work associated with human activity, which gained special importance since the industrial revolution” (Velasco-Fernández et al., 2014). The key concept underpinning the phrase “exosomatic metabolism” (Lotka, 1956; Georgescu-Roegen, 1975; Giampietro et al., 2009) is thus that, as a society develops and becomes further and further removed from a basic hunter-gatherer one, the share of its overall energy demand that is required for non-primary biological needs (i.e., for its *exo*-somatic metabolism) becomes larger and larger compared to the share thereof that is instead directly required for supporting the primary biological needs of its people (i.e., for its *endo*-somatic metabolism).

The exact quantification of what may be considered a ‘sufficient’ NEG is still the object of much speculation, and in fact largely depends on the specific demand for different kinds of ECs dictated by the existing network of intertwined energy supply chains that characterize each individual country (International Energy Agency (IEA), 2014c). As a result, different *minimum* NEGs may be identified for each type of EC in each country.

We therefore argue that it is important to ‘benchmark’, as we do hereinafter, the net energy performance of all extant electricity production technologies in the country of interest against the current average performance of the mix of technologies (i.e., the grid mix) that at the same time provides that same country with electricity.

Adopting the cautionary principle, any future changes to the mix of technologies that make up a country’s grid mix should at least ensure that the grid’s current overall NEG be maintained; a higher projected NEG would then guarantee a larger safety ‘buffer’ against unforeseen changes in demand. Looking at the situation from the opposite end, if instead major large-scale changes were made to a country’s grid mix which quickly resulted in an insufficient overall NEG to satisfy the societal electricity consumption patterns in the short term, then the ensuing scarcity of disposable energy surplus would severely limit the country’s ultimate ability to afford staying on the path of a long-term transition to a more sustainable electricity supply mix.

At the same time, though, NEA does not differentiate between renewable and non-renewable energy sources. Even when two systems are characterised by the same NEG, one may still lead to a faster deployment of non-renewable PES than the other, if its NEG is achieved mainly by depleting non-renewable primary energy stocks *vs.* harvesting renewable primary energy flows. Thus, basing long-term energy policy recommendations on the insight provided by NEA alone risks overlooking the extent to which the current societal energy (and, specifically, electricity) supply and consumption patterns may actually be *inherently* unsustainable in the long run (as all those relying heavily on non-renewable PES ultimately are).

1.4. Life Cycle Assessment (LCA)

Not unlike NEA, life cycle assessment (LCA) too is a discipline that has its roots in a number of studies conducted in the 1960’s and 70’s aimed at optimising energy consumption in a context where the latter represented a restraint for the industry (e.g. Hunt et al., 1974). Since then, LCA has been further developed and standardised (Consoli et al., 1993; Lindfors et al., 1995; ISO, 2006a, 2006b; European Commission, 2010a, 2010b), but its core aim has always remained to understand the overall environmental impacts of a product or system along its full life cycle (from the extraction of the necessary primary resources, to end-of-life disposal and, where applicable, recycling). Accordingly, LCA’s energy demand metrics look at the *total primary energy that must be harvested* from the environment in order to produce a given amount of usable product or EC (Frischknecht et al., 1998, 2007, 2015a, 2015b). LCA also makes a clear distinction between renewable and non-renewable energy sources and flows, and keeps separate accounts of the two at all times. (Besides energy, LCA also addresses a number of other environmental impact categories, such as global warming, ozone depletion, human and eco-toxicity, etc., but these will not be discussed further here as they fall outside of the intended scope of this paper).

LCA’s focus on the total primary energy harvested (also referred to as *cumulative energy demand* or CED) provides a valuable counterpoint to NEA’s emphasis on the utilitarian concept of *energy surplus*. In fact, it may be said that while NEA provides a means to rank a range of alternative energy (and specifically, electricity) production technologies in terms of their *effectiveness* at exploiting PES and upgrading stocks and flows of primary energy into a directly usable EC (thus providing the needed energy surplus to support a society's exosomatic metabolism), LCA allows the ranking of the same technologies according to their ultimate degree of *energy sustainability*, the latter being inversely proportional to their overall demand for (and therefore contribution to the depletion of) non-renewable primary energy.

1.5. Goal and scope of the present analysis

The overarching goal of the body of work presented in this paper was the comparison of the energy performance of the full range of currently employed electricity production technologies in the United Kingdom.

In order to ensure internal consistency, all the performance indicators were calculated on the basis of the same set of underlying life cycle inventories (LCI) for the analysed technologies. The main data source was the reputable Ecoinvent database (Ecoinvent Centre for Life Cycle inventories (Ecoinvent), 2014), integrated wherever needed by other literature sources in order to adapt the information to the best possible extent to the actual conditions for the UK. No material or energy inputs were estimated indirectly by means of economic input-output tables (Leontief, 1985; Bullard et al., 1978) or otherwise converted from monetary units to physical units by means of ‘energy-to-money’ ratios.

End-of-life (EoL) management of the wind and PV power plants on decommissioning was not included in the analysis because of the heretofore dearth of reliable related information, due to the relatively recent large-scale introduction of these technologies to the energy market. However, the eventual inclusion of EoL management within the respective system boundaries is not likely to negatively impact the overall energy performance of these technologies, given the energy credits afforded by the relatively easy recycling of large quantities of valuable metals such as copper, aluminium and steel, even when assuming the latter's likely down-cycling into the respective quality-adjusted average market mixes of primary and secondary sources (Bala Gala et al., 2015).

Finally, the decision was made not to include any form of energy storage within the system boundaries for any of the analysed technologies. This is because many electricity production technologies (including renewables like PV and wind, *as well as* baseload technologies such as large coal-fired[1] and nuclear facilities) are in fact not able to single-handedly follow the dynamic pattern of societal electricity demand, and, if deployed on their own, they would all require *some* storage capacity in order to do so. That being the case, it would only be meaningful to address the issue of energy storage when analysing and comparing alternative scenarios at the level of a country's grid mix, rather than at the level of each individual technology *per se* (Carbajales-Dale et al., 2015), and while also taking into consideration the smoothing effect produced by combining PV with wind (Nikolakakis and Fthenakis, 2011), and the buffering capacity provided by flexible gas turbines.

2. Methodology

The choice was made to jointly apply NEA and LCA, so as to capture both viewpoints offered by these two disciplines, and enable a balanced discussion of the results in terms of short-term energy effectiveness and long-term energy sustainability.

Fig. 1 schematically illustrates the two main existing classes of electricity generation systems. Diagram [A] refers to a thermal system relying on a feedstock supply (of coal, oil, gas, biomass or nuclear fuel), and diagram [B] refers to a system directly harvesting a renewable primary energy flow (of hydro, wind, or solar energy).

The following definitions apply:

- PE = primary energy directly harvested from the PES, which in the case of system [A] also includes that co-extracted but then 'lost' to the environment (Arvesen and Hertwich, 2015).
- Inv = total energy investment required to: (i) build, operate and decommission the power plant (applies to systems [A] and [B]), and (ii) extract, deliver and refine the feedstock (applies to system [A] only).
- Out = total energy produced.

At this point it is important to discuss the units in which these three key energy flows are measured.

'PE' is obviously measured in units of primary energy [MJ_{PE}], and the most common practice in the literature is to express these on a Higher Heating Value (HHV) basis, i.e., including, when applicable, the latent heat of the water vapour generated during combustion (Frischknecht et al., 2007). This convention was adopted here too.

'Inv' is the total energy *diverted from other possible societal uses*, and as such it is supplied to the system as a combination of readily-available energy carriers. However, just summing the individual amounts of energy carriers that comprise the total investment in their respective units (i.e., [MJ_{th}] or [MJ_{el}]) would correspond to only accounting for those energy investments that would be characterized as 'foreground'[2] inputs in LCA. While occasionally adopted by some authors (Weißbach et al., 2013), such reduced system boundaries would result in: (i) the inconsistent sum of a range of investments which are supplied as different and not directly comparable energy carriers such as liquid fuels and electricity (Raugei et al., 2015); and (b) the exclusion of a number of potentially significant energy investments which take place in the system's 'background'. In order to avoid such inconsistencies and maintain full life-cycle system boundaries, we adopted the widely accepted methodological convention (Arvesen and Hertwich, 2015) to express all energy investments in terms of their respective CED, measured in [MJ_{PE}].

'Out' may either be accounted for in direct energy units of the delivered energy carrier ('Out_{el}' measured in [MJ_{el}]), or in terms of its *equivalent* primary energy ('$Out_{PE\text{-}eq}$' measured in [MJ_{PE}]). The

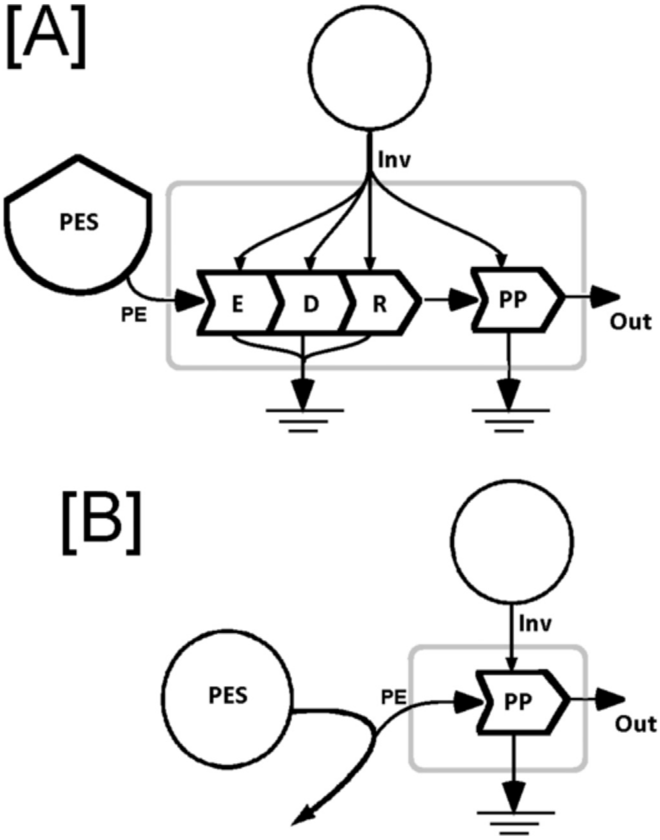

Fig. 1. Streamlined energy systems diagrams of [A] a thermal electricity production system (coal-, oil-, gas-, biomass- or nuclear-fuelled), and [B] a renewable electricity production system (hydro, wind or PV). PES = primary energy source; E = feedstock extraction; D = feedstock delivery; R = feedstock refining; PP = power plant. Symbolic conventions after Odum, 1983.

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[1] While coal-fired power plants may in principle be adapted to function in a responsive (load-following) way, this often entails penalties in terms of additional cost and sometimes also reduced reliability, and as a result it is often only practical for the smaller stations. As of 2013 (Department of Energy & Climate Change (DECC), 2014a), 94% of coal power plants in the UK were large/baseload (> 1000 MW installed capacity) and only 6% were small/flexible (< 1000 MW).

[2] The LCA definition of 'foreground' refers to those processes "…that are under direct control of the producer of the good or operator of the service, or user of the good or where he has decisive influence… This covers firstly all in-house processes of the producer or service operator of the analysed system. Secondly… also all processes and suppliers of purchased made-to-order goods and services, i.e., as far as the producer of service operator of the analysed system can influence them by choice or specification".

By contrast, background data "…comprises those processes that are operated as part of the system, but that are not under direct control or decisive influence of the producer of the good (or operator of the service, or user of the good). The background processes and systems are hence outside the direct influence or choice of the producer or service operator of the analysed system" [European Commission, 2010a, p. 97–98].

conversion from Out_{el} to $Out_{PE\text{-}eq}$ is performed on the basis of a widely agreed-upon equivalency relationship, which follows a replacement logic akin to that used in LCA: one unit of electricity produced by a specific technology is assumed to displace (and hence be equivalent to) the same amount of electricity produced by the current grid mix (G) in the country of interest. Operationally, we thus have:

$$Out_{PE-eq} = Out_{el}/\eta_G$$

where η_G is the life-cycle energy efficiency of the grid mix, i.e., the ratio of the grid's yearly electricity output [MJ_{el}] to the total primary energy harvested from the environment for its operation, allocated to the same year [$MJ_{PE\text{-}eq}$] (in other words, $\eta_G=1/CED_G$).

Only when both Inv and $Out_{PE\text{-}eq}$ are expressed in terms of (equivalent) primary energy, may the NEG be defined in strictly consistent units as:

$$NEG = Out_{PE-eq} - Inv$$

Based on the definitions above, the following NEA indicators may be calculated:

- $EROI_{el}=Out_{el}/Inv$=energy return on investment, in terms of direct electricity.
- $EROI_{PE\text{-}eq}=Out_{PE\text{-}eq}/Inv= EROI_{el}/\eta_G$=energy return on investment, in terms of equivalent primary energy.
- $NTG=NEG/Out_{PE\text{-}eq}$=net-to-gross energy output ratio, in terms of equivalent primary energy.
  $EROI_{el}$ is an 'absolute' indicator of the performance of each analysed technology; however, since "the numerator and the denominator are not measured by the same rule, one loses the intuitively appealing interpretation that EROI > 1 is the absolute minimum requirement a resource must meet in order to constitute a net energy source" (Arvesen and Hertwich, 2015).
  $EROI_{PE\text{-}eq}$ is instead an intrinsically'relative' indicator, in that its numerical value depends not only on the actual energy performance of the system under study, but also on that of the electric grid that it is assumed to (partially) replace. Any observed change in the $EROI_{PE\text{-}eq}$ of a given technology over time may therefore depend not (or not only) on a change in electricity output per unit of energy investment, but also on a change in the average life-cycle efficiency of the grid (η_G)[3].
  Based on the same set of definitions and conventions, the two main energy demand indicators used in LCA may also be defined as follows for electricity production systems:
- $CED=(PE+Inv)/Out_{el}$=cumulative primary energy demand per unit of electricity output (Frischknecht et al., 1998; 2007; 2015a).
- nr-CED= non-renewable cumulative primary energy demand per unit of electricity output (corresponding to the non-renewable share of the CED).

Given the relevance of the demand for non-renewable energy for the long-term sustainability of an energy supply chain, we shall focus hereinafter specifically on nr-CED.

3. Data

Sub-Sections 3.1–3.8 contain brief descriptions of the key aspects of the analysed electricity production technologies. Detailed calculation tables for all technologies are provided in the Supplementary Information, available via the Internet at: http://www.sciencedirect.com.

3.1. Coal electricity

Until the 1960s, the UK's demand for coal was almost entirely met by domestic production (Department of Energy & Climate Change (DECC), 2013a). The situation has since radically changed, and over the last forty years coal imports have played an ever larger role; in 2013 almost all the UK coal supply was imported, with 90% thereof coming from three countries: Russia, the USA and Colombia (Department of Energy & Climate Change (DECC), 2015a). In all three countries, and especially Russia and Colombia, a large share of the coal is extracted by surface mining (Energy Information Administration (EIA), 2013, 2015a, 2015b), which requires the removal of large amounts of overburden and entails considerable environmental impact. Coal-fired electricity production is a mature technology that is not expected to undergo major changes in the coming decades, except for the possible retro-fitting of carbon capture and storage (CCS) equipment, which is however still only at the project proposal stage in the UK (Carbon Capture & Storage Association (CCSa), 2015).

3.2. Oil electricity

Approximately 20% of the UK's demand for crude oil is met by domestic off-shore production in the North Sea, with the rest coming mainly from Algeria, Nigeria and Norway (Department of Energy & Climate Change (DECC), 2014b). After being transported to the UK mainland by oceanic tankers, the crude oil is refined (mostly at 8 major refineries in England, Wales and Scotland (O'Born, 2012)) into a number of co-products, of which the heavy fuel oil (HFO) used for electricity generation represents approximately 10% by mass (Department of Energy & Climate Change (DECC), 2015a). The allocation of the overall energy investment and CED for the refining operations to the refinery co-products was done on the basis of their average energy content (Jungbluth, 2007). Oil-fired electricity production is also technologically mature; its current share of the UK grid mix is however very small, and it is planned to be phased out almost completely in all future scenarios drafted by National Grid (2014a).

3.3. Gas and gas combined cycle electricity

As recently as in 2000, UK natural gas was almost entirely sourced from domestic off-shore deposits in the North Sea; from that year onwards, the level of imports has progressively increased as UK domestic supplies have declined (Whitmarsh et al., 2012; National Grid, 2014b). In 2013, less than half of the total UK supply of natural gas was domestic, while most of the rest was imported from Norwegian off-shore deposits and, in a smaller measure, from the Netherlands via the Balgzand Bacton Line (a recent purpose-built natural gas interconnector between the two countries, mainly delivering gas from the on-land Groningen field in the NL (Whaley, 2009)). Transport of natural gas via pipeline entails inevitable losses, which were accounted for in our analysis using Ecoinvent's estimates. Approximately 10% of the overall gas imports to the UK in 2013 were also supplied in liquefied form (LNG), mainly from Qatar (National Grid, 2014b); due to the unavailability of detailed inventory data for Qatari operations, this small percentage was however disregarded in our analysis. Finally, the exploitation of domestic non-conventional gas deposits found in onshore shales is planned but not yet operational (National Grid, 2014b); given the different nature of these deposits and of the

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[3] Incidentally, as discussed elsewhere (Raugei, 2013), the same consideration also applies to the Energy Pay-Back Time (EPBT) indicator (Fthenakis et al., 2011), which is often used when reporting on the energy performance of PVs and other renewable technologies.

technology required to exploit them, it is not possible to extrapolate information on the associated energy investment from the existing datasets. Both conventional and combined cycle gas-fired electricity production are mature technologies; the former is however much more widespread, and it benefits from a higher overall feedstock-to-electricity conversion efficiency thanks to the secondary exploitation of the heat produced in the gas combustion process.

3.4. Biomass electricity

The term biomass encompasses a large variety of materials, including wood from various sources, agricultural residues, and animal and human waste. Three main types of biomass are used for electricity production in the UK: wood chips, wood pellets and straw (Department of Energy & Climate Change (DECC), 2014c). Both the wood chips and straw are sourced domestically, while the wood pellets are imported from North America (mainly the USA). Mass-based allocation was used for all multi-output processes in the supply chains of these feedstocks. All three biomass feedstocks are then directly combusted in thermal power plants, which are often former coal power plants converted to use biomass (Department of Energy & Climate Change (DECC), 2014c).

3.5. Nuclear electricity

UK national data for uranium imports are not directly available (UK parliament, 2010). The UK supply mix was therefore assumed to be the same as that for the EU as a whole, which in 2013 was mainly from Kazakhstan, Canada, Russia, Nigeria and Australia (European Commission, 2014). Canadian uranium mostly comes from underground mines (Canadian Nuclear Association, 2015), while open-pit mining and in-situ leaching (ISL) are also common elsewhere (World Nuclear Association, 2015a). No detailed process information was available for ISL, though, and as a result the production of ‘yellowcake’ (the name given to the marketable U ore concentrate) in all other countries beside Canada was modelled on the basis of 50% open-pit and 50% underground mining. To produce fissile fuel, uranium oxide is converted to UF_6 and subject to an ‘enrichment’ process whereby the concentration of the ^{235}U isotope is increased. Historically, U enrichment was performed by diffusion, but this process has now been almost completely displaced by the more efficient centrifuge method (World Nuclear Association, 2015b). Mixed oxide (MOX) nuclear fuel obtained by recycling and re-processing spent fuel is not currently used in the UK (European Commission, 2014). Of the sixteen nuclear reactors in operation in the UK (UK government, 2015), fourteen are advanced gas-cooled reactors (AGR) built between the late 1970s and 1980s, one is a newer pressurised water reactor (PWR), and one an even older Magnox reactor (which was scheduled to be decommissioned by the end of 2014 (Berkemeier et al., 2014), but which was then given a one-year extension (BBC, 2014)). Of these three reactor types, detailed life-cycle inventory information was only available for the more common PWR, which was therefore used as the model of choice in our study. The AGR and Magnox reactors are peculiar British designs, which are similar to but somewhat more complex than PWRs, and their production may have entailed a larger energy investment. On the one hand, our results may therefore be looked at as a ‘best case’ estimate of the current performance of nuclear electricity in the UK. On the other hand, however, all but one of the AGR reactors are due for retirement within the next decade, and most future nuclear power plants to be built in the UK are planned to be of the PWR type (Nuclear Advanced Manufacturing Research Centre (NAMRC), 2015); our results may thus still be considered quite relevant in terms of their energy policy implications.

The end-of-life treatment of the spent nuclear fuel and of the other highly and intermediate long-lived radioactive wastes was modelled according to the information available in Ecoinvent (2007); in particular, the modelling of the final repositories is based on a Swiss demonstration project (Nagra, 2002a, 2002b), which inevitably entails some degree of uncertainty.

From a methodological point of view, it is important to note that the “standard” computation of the CED (and nr-CED) of uranium does not include: (i) the energy content in the depleted uranium (‘tail’) from the enrichment process, and (ii) the energy content in the ^{235}U remaining in the spent fuel at its final discharge from the reactor (Frischknecht et al., 2007). Higher CED (and nr-CED) values for uranium which also include these contributions are available, and have been referred to as “Uranium high” (Frischknecht et al., 2015a). In this study, both alternatives were considered, and the nr-CED results for nuclear electricity corresponding to the use of the “Uranium high” approach have been reported as part of the sensitivity analysis.

3.6. Hydro electricity

Three types of hydroelectric power plants are in use in the UK: large-scale conventional and pumped storage systems, where a dam impounds water in a reservoir that feeds the turbine, and small-scale run-of-river units, where the natural flow of a river or stream is used to drive the turbine (Department of Energy & Climate Change (DECC), 2013b). Pumped storage output is however not considered part of the electricity generation mix, since it relies on electricity in the first place in order to pump the water up into the reservoir at times of low demand.

Given that the only energy investment required for hydroelectricity is that for the power plant, the $EROI_{el}$ ends up being directly proportional to its estimated lifetime. We therefore deemed it important to carry out a sensitivity analysis, whereby the lifetime of the hydroelectric power plants was allowed to vary in a +/-25% range with respect to the chosen reference value of 80 years (Dones et al., 2007). Also, in order to account for the intrinsic variability of meteorological conditions and their effect on the capacity factor (CF, defined as the ratio of the actual average power output to the nominal installed power), we carried out a sensitivity analysis whereby the CF was allowed to vary between the minimum and maximum values recorded over the 2009–2013 five-year period (Department of Energy & Climate Change (DECC), 2014a).

These same considerations in terms of lifetime and CF also apply to all other electricity production systems that harvest renewable energy directly (*cf.* Fig. 1 [B]), which were therefore subject to a similar sensitivity analysis, resulting in corresponding ‘uncertainty bars’ in all Figures in Section 4.

3.7. Wind electricity

Both on shore and off-shore wind turbines are deployed in the UK, with a 2.3:1 ratio of respective installed capacities in 2013 (Department of Energy & Climate Change (DECC), 2014a). For both types of systems, a reference 20 year lifetime was assumed as per Ecoinvent, with the only exception of a longer (40 year) lifetime for the fixed parts of on shore installations (Dones et al., 2007). A 30 year lifetime was then considered as part of the sensitivity analysis, as suggested by Garret and Rønde, 2013. The capacity factor was also allowed to vary between the minimum and maximum values recorded over the 2009–2013 five-year period (Department of Energy & Climate Change (DECC), 2014a).

3.8. PV electricity

Approximately half of the cumulative installed PV capacity in the UK in 2013 was in the form of residential and commercial rooftop-mounted systems (European Photovoltaic Industry Association (EPIA), 2014), partly in response to the feed-in tariff scheme for small-scale (< 5 MWp) installations of low-carbon technologies (Department of Energy & Climate Change (DECC), 2015b). The vast majority of the installed PV systems use multi- and single- crystalline silicon (c-Si) modules (Fraunhofer, 2014); the latter are more efficient but more energy-intensive to produce as they require additional recrystallisation (Czochralski process). The feedstock for the production of the PV cells used to be sourced from scrap electronic-grade Si, but this has been almost completely displaced by the sector-specific supply of solar-grade Si (Jungbluth et al., 2012), a large share of which is currently produced in China (Bloomberg, 2014). A few ground-mounted CdTe thin film PV installations are also starting to appear (Renews, 2014), and it was deemed interesting to include this relatively novel technology in the analysis as well. Given the rapid pace of change in the PV industry and the remarkable sustained improvements in terms of both module efficiency and energy demand for production (Siemer and Knoll, 2013; International Energy Agency (IEA), 2014d), we deemed it appropriate to base our analysis on the latest published data for current-generation systems in 2013 (de Wild-Scholten, 2013; Frischknecht et al., 2015b). Specific data for ground-mounted balance of system (BOS) components were sourced from Mason et al., 2006. A reference system lifetime of 30 years was assumed (Fthenakis et al., 2011), with a sensitivity analysis extending the range from 25 years (the typical manufacturer-guaranteed lifetime) to a best-case projection of 40 years, which is still considered to be easily attainable by some manufacturers (SunPower, 2013). Irradiation levels were allowed to vary between the minimum and maximum for the UK (European Commission, 2012), with a mean reference value of 1000 kWh/(m^2*yr).

4. Results and discussion

Fig. 2 (note use of logarithmic vertical axis) illustrates the resulting EROI$_{el}$ of all analysed technologies, alongside the value for the UK electric grid as a whole. The latter was calculated as:

$$\text{EROL}_{el,G} = 1/[\ \textstyle\sum_i (\omega_i/\text{EROL}_{el,i})]$$

where ω_i is the share of total grid output supplied by technology i, and EROI$_{el,i}$ is the EROI$_{el}$ of the same technology.

The range spanned by the EROI$_{el}$ results is rather large, with the lower end set by biomass-fired thermal electricity at a very low 1.1 (and with oil-fired electricity not far off at 1.7), and the higher end by hydroelectricity (avg. estimate = 58). Right after hydro, a cluster of well-performing technologies (EROI$_{el}$ > 10) may be identified, comprising gas-fired, nuclear and wind electricity. Lagging slightly behind then comes CdTe PV, which however still performs better than the grid mix average, while c-Si PV joins coal-fired electricity towards the lower end of the range.

The very low EROI$_{el}$ of biomass-fired electricity largely depends on the mix of fuels used. For instance, as shown in Table S5 in the Supplementary Information, domestic wood chips have an initially high EROI of over 50 [MJ$_{th}$/MJ$_{PE}$]. However, availability constraints dictate that domestic wood chips only account for ~40% of the biomass used in power plants in the UK. At the other end of the scale, wood pellets imported from the USA start out with a very low EROI of ~3 [MJ$_{th}$/MJ$_{PE}$] at the source. This large difference is mostly due to the additional processing required to produce the pellets. The issue is then compounded by the additional energy investment needed to transport the pellets from the USA to the UK. Finally, the EROI$_{el}$ of biomass-fired electricity is also negatively affected by the relatively low efficiency with which the feedstock is converted to electricity in the power plant (~24%).

But perhaps the most remarkable and unexpected results are the low values for oil- and coal-fired electricity, especially when compared to the previously available estimates. This is due to two main reasons. Firstly, the EROI of the fossil fuels at their respective sites of extraction in the countries from which they are imported

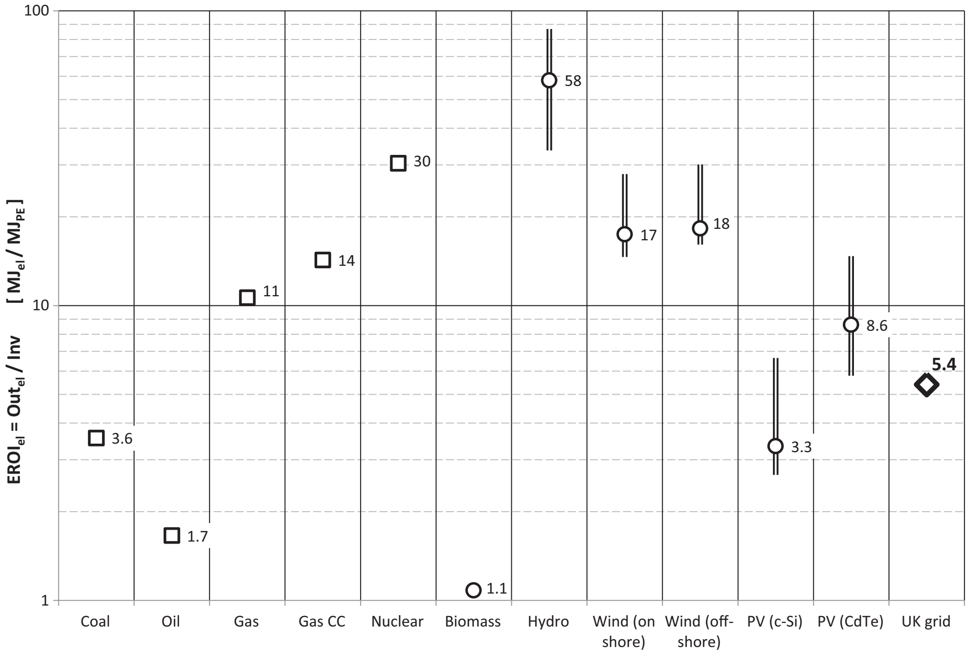

Fig. 2. EROI$_{el}$ of all non-renewable (square symbols) and renewable (round symbols) electricity generation technologies deployed in the UK, and overall value for the UK grid as a whole (diamond symbol). Values for hydro, wind and PV technologies include sensitivity analysis to account for variability in capacity factors and uncertainty in expected lifetimes.

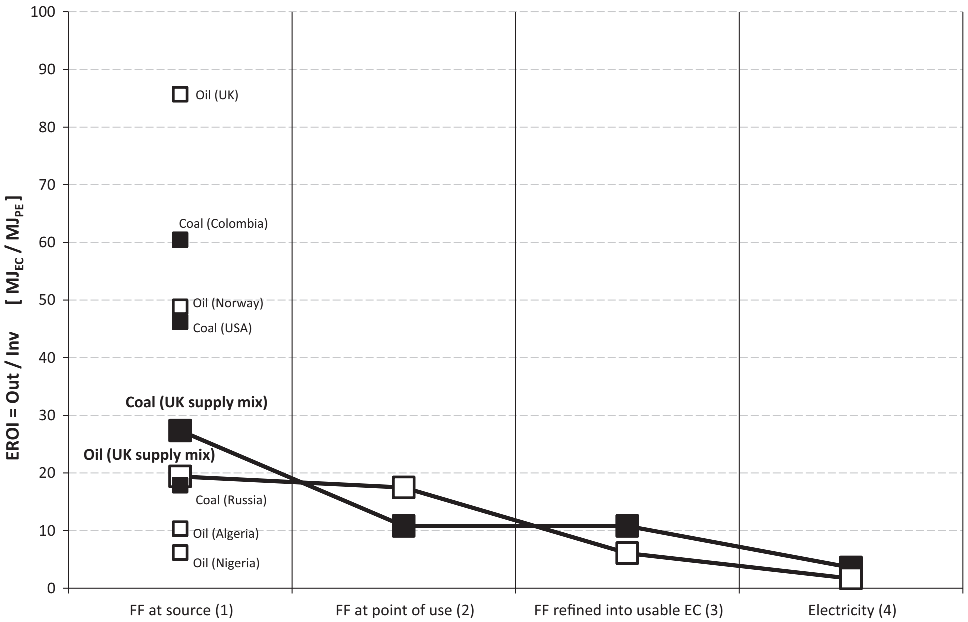

Fig. 3. EROI (direct output of energy carrier over investment of equivalent primary energy) of coal (black squares) and oil (white squares) along the successive stages of their supply chains to the UK, from extraction (1), on to delivery (2), refining (3), and conversion into electricity at the power plant (4).

into the UK were found to be sometimes considerably lower than what might have been expected based on their generally accepted historical ranges. This was especially the case for African oil and Russian coal. Secondly, as illustrated in Fig. 3, it became apparent that the energy investment for the long-distance transport required to deliver the fuels to the UK mainland (especially for coal), and those for their refining and processing (for oil[4]), take a considerable toll on the final EROI of the usable feedstocks.

Previous estimates of the $EROI_{el}$ of thermal electricity that were calculated starting from the average literature values for the EROI of the fossil fuels at source and only accounting for the power plant heat rate and the additional energy investment to build and operate it (including those made by one of the authors (Raugei et al., 2012)) were therefore probably too optimistic, especially in the case of countries that do not have locally exploitable reserves of those same fuels.

Fig. 3 highlights the potentially misleading nature of a direct comparison of the EROI of different energy sources, unless the conditions of the analyses are very clearly and consistently defined. Firstly, such wide-ranging comparisons should only be performed for functionally equivalent ECs (e.g., either thermal fuels or electricity, but not both at the same time); and secondly, in the case of a comparison amongst fuels, the latter should be sampled at equivalent stages of their respective supply chains. Failing to do so and comparing, for instance, crude oil to PV electricity puts the latter at a double disadvantage, since (i) the crude oil needs to be transported and converted into an EC (such as HFO) before it can be used, and (ii) no fewer than approximately three units of HFO are then required to produce one unit of electricity. While this fact has been recognised and discussed before (Hall et al., 2014; Lambert, Lambert, 2013), unfortunately the literature is still populated by widely cited 'balloon graphs' (Hall et al., 2008; Murphy and Hall, 2010) and bar charts (Hall and Day, 2009) where results for poorly-defined systems such as "coal" or "oil" are presented alongside those for other technologies whose only possible output is electricity. Referring to the case of coal-fired electricity in the UK as a practical example, our analysis has shown that the average EROI=27 $[MJ_{th}/MJ_{PE}]$ of 'raw' coal at the extraction sites in the supplying countries (*cf.* Fig. 3 and Table S1 in the Supplementary Information) shrinks to $EROI_{el}=3.5$ $[MJ_{el}/MJ_{PE}]$ (i.e., almost one order of magnitude lower) by the time the fuel has been delivered, refined and converted into electricity. Clearly, it is the latter figure, and not the former, which should be compared to the $EROI_{el}$ of other competing electricity production technologies in the same country.

It is then even more important to keep in mind that, from the point of view of NEA, what is ultimately important is the available NEG, and the directly related NTG. As discussed in Section 2, NEG and NTG may only be strictly defined when both the energy investment (Inv) and the delivered energy carrier (Out_{PE-eq}) are expressed as (equivalent) primary energy. It is easy to verify that:

$$NTG = (EROI_{PE-eq} - 1)/EROI_{PE-eq}$$

This is a well-known non-linear relation which has been discussed in the literature before, and the resulting sloping line has been referred to as the 'net energy cliff' (Murphy and Hall, 2010). However, previous mentions of it have often left it unclear whether the NTG was calculated correctly (i.e., with all factors accounted for in consistent units of primary energy) or incorrectly (i.e., inconsistently mixing and matching units of different energy carriers and/or primary energy). As discussed above, comparing the relative positions on the 'cliff' of different energy sources at different and non-equivalent stages of their respective supply chains is ultimately meaningless. Also (*cf.* Section 1.3), the generalised concept of the "minimum EROI that a sustainable society must have" (Hall et al., 2009) remains inescapably fuzzy unless it is clearly contextualised, both in terms of the specific type of EC under scrutiny (e.g., liquid fuels, electricity, etc.) and the specific demand for it dictated by the exosomatic metabolism of the individual society being considered.

Fig. 4 illustrates the relative positions of all the electricity generation technologies deployed in the UK on the 'net energy cliff'. A vertical line is also drawn to indicate the average performance of the UK grid as a whole.

The first clear consequence of the strong non-linearity of the

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[4] Interestingly, our results for the energy investment required for the operation of the oil refinery are remarkably in line with those produced by a recent independent study focussing on the efficiency of oil production in California (Brandt, 2011).

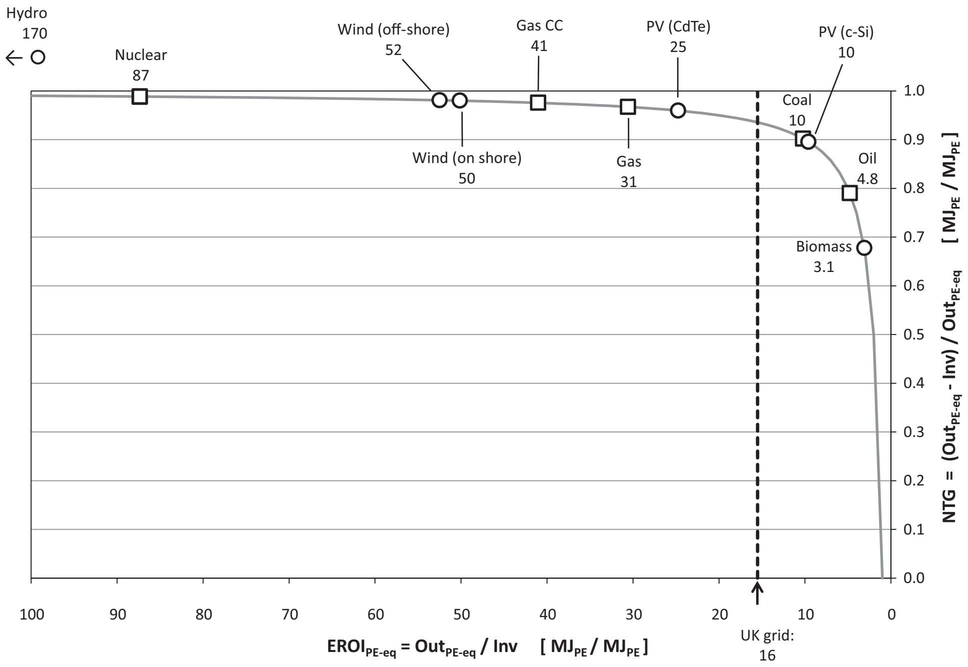

Fig. 4. 'Net energy cliff' illustrating non-linear relation of NTG to EROI$_{PE\text{-}eq}$, with values for all non-renewable (square symbols) and renewable (round symbols) electricity generation technologies deployed in the UK, and threshold set by overall EROI$_{PE\text{-}eq}$ of the UK grid as a whole (dashed line).

relation between NTG and EROI$_{PE\text{-}eq}$ is that differences between individual EROI$_{PE\text{-}eq}$ values result in markedly different NTGs when the absolute EROI$_{PE\text{-}eq}$ values are small, whereas such differences become less and less consequential as the absolute EROI$_{PE\text{-}eq}$ values become larger. For instance, while the jump from EROI$_{PE\text{-}eq}=3.1$ (biomass electricity) to EROI$_{PE\text{-}eq}=10$ (coal electricity) results in a marked improvement of the NTG (from 0.68 to 0.90), the difference between EROI$_{PE\text{-}eq}=52$ (off-shore wind electricity) and EROI$_{PE\text{-}eq}=87$ (nuclear electricity) only results in a comparatively insignificant increase of the NTG (from 0.98 to 0.99).

The performance of the UK grid as a whole is characterised by $\eta_G=0.35$ and EROI$_{PE\text{-}eq}=16$, which corresponds to NTG=0.94. *This latter value may be regarded as the minimum 'necessary' NTG that must be maintained in order to ensure the continued support of the current demand for net energy supplied to the UK society in the form of electricity*. The positions of the individual electricity generation technologies on the curve relative to such 'threshold' may then be understood to indicate which technologies have more (towards the upper left) or less (towards the lower right) potential for supporting the UK society's demand for net energy when embarking on a transition to a different grid mix.

As a necessary complement to the assessment of the net energy performance of the analysed technologies, Fig. 5 then presents the results of the calculation of their respective nr-CED, indicative of their long-term energy sustainability (note use of logarithmic vertical axis).

As expected, all the technologies conventionally referred to as 'non-renewable' require more than one unit of non-renewable primary energy per unit of delivered electricity. Also unsurprisingly, the nr-CED of the thermal technologies is largely determined by the feedstock-to-electricity conversion efficiency of the power plant (also referred to as heat rate), which is ultimately limited by the Carnot ratio and often lies in the vicinity of 1/3 (combined cycles fare marginally better due to the secondary exploitation of the post-combustion waste heat).

It is interesting to note that biomass-fired electricity, despite being nominally a 'renewable' technology, still requires almost 0.9 units of non-renewable primary energy per unit of delivered electricity, due to the energy investments needed to harvest, process and deliver the feedstocks.

All other renewable electricity production technologies are then at least one order of magnitude less intensive in their demand for non-renewable primary energy, with hydroelectricity once again in a leading position with just 0.016 MJ$_{PE\text{-}eq}$/MJ$_{el}$.

Finally, Fig. 6 presents a novel, and arguably also the most insightful, way to synthetically illustrate and compare the all-round energy performance of all analysed electricity generation technologies. In it, the two key indicators discussed above, i.e., NTG (responding to the NEA logic) and nr-CED (responding to the LCA logic), are used to define a two-dimensional virtual space. This allows a clear visual depiction of any inherent trade-offs in terms of the technologies' short-term energy effectiveness (as measured by NTG) *vs.* long-term energy sustainability (as measured by nr-CED), as well as an equally clear indication of the potential for Pareto improvements[5] brought about by replacing one technology with another.

The overall values of the two indicators for the UK grid as a whole are also plotted as two dashed lines representing thresholds that define four quadrants. Since the horizontal nr-CED axis is oriented from right to left (also note use of logarithmic scale), the two right quadrants contain those technologies whose demand for non-renewable primary energy per unit of delivered electricity is lower than that of the UK grid as a whole. Similarly, the two upper quadrants contain those technologies that provide a larger unit energy surplus (higher NTG) than average for the UK grid mix. As a result, only the technologies positioned in the upper right quadrant simultaneously fulfil both conditions, and may therefore be regarded as delivering a 'better' all-round energy performance with respect to the current UK grid mix.

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[5] A Pareto improvement is one in which a change to a system results in an improvement in at least one of its parameters/criteria without at the same time making any of the other parameters/criteria worse.

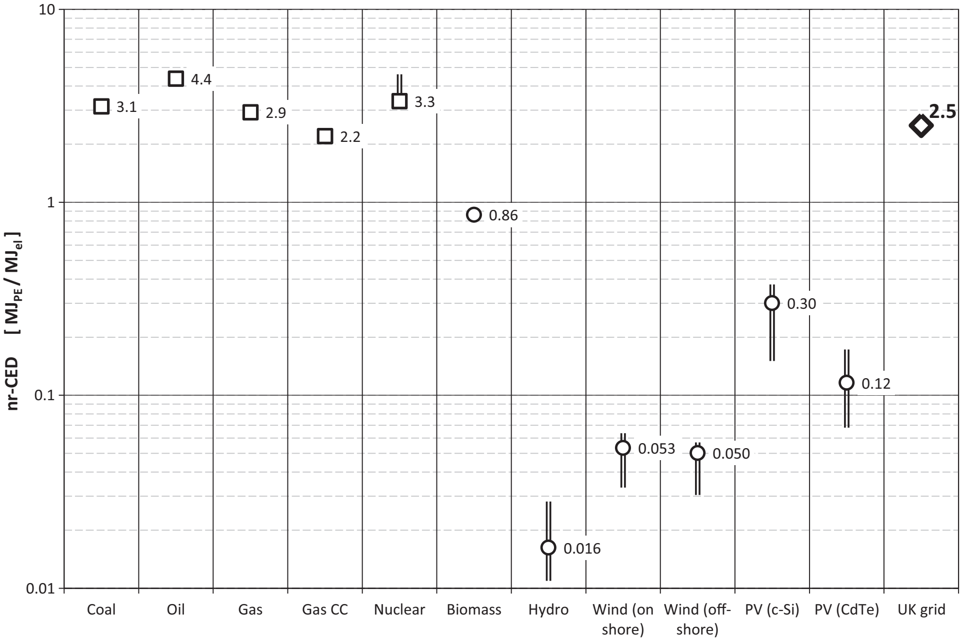

Fig. 5. nr-CED of all non-renewable (square symbols) and renewable (round symbols) electricity generation technologies deployed in the UK, and overall value for the UK grid as a whole (diamond symbol). Values for nuclear, hydro, wind and PV technologies include sensitivity analysis to account for, respectively: alternative accounting methods for the CED of uranium (nuclear), and variability in capacity factors and uncertainty in expected lifetimes (hydro, wind and PV).

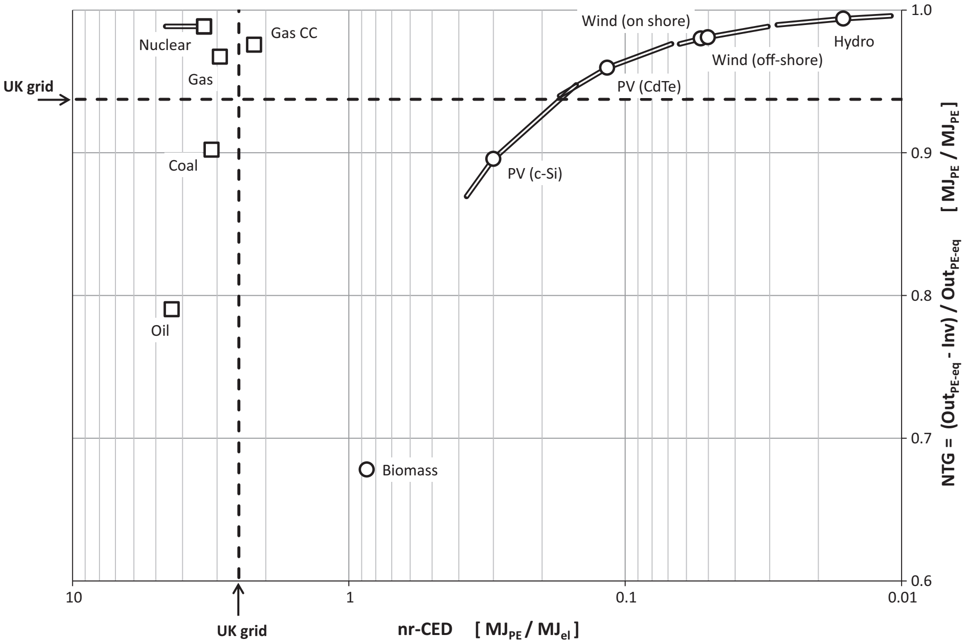

Fig. 6. Positioning of all non-renewable (square symbols) and renewable (round symbols) electricity generation technologies deployed in the UK in the two-dimensional space defined by nr-CED (horizontal axis) and NTG (vertical axis). The overall values of the two indicators for the UK grid as a whole (dashed lines) define four quadrants, of which the right upper one contains those technologies whose combined performance w.r.t the two indicators is better than that of the grid itself. Values for nuclear, hydro, wind and PV technologies include sensitivity analysis to account for, respectively: alternative accounting methods for the CED of uranium (nuclear), and variability in capacity factors and uncertainty in expected lifetimes (hydro, wind and PV).

Fig. 6 makes it clear that, in the UK, coal- and oil-fired electricity generation are the least desirable technologies overall, in terms of both their inefficient use of non-renewable primary resources and their comparatively low NTG ratios (the latter partly determined, as discussed before, by the necessity to import the fuels from distant overseas suppliers). Oil-fired electricity is only a very minor contributor to the UK grid mix already, but the share of coal-fired electricity is instead the largest in the mix (*cf.* Table 1). This gives pause for reflection, and appears to be a clear indication that phasing out coal-fired electricity should be a top priority in all future scenarios of grid improvement.

Another outlier in Fig. 6 is biomass-fired electricity, which, despite a somewhat better performance in terms of renewability, is burdened by a high energy investment per unit of output, which results in a hopelessly low NTG ratio.

On the contrary, nuclear electricity performs very well in terms of net energy (featuring one of the highest NTGs), but it is no more sustainable than oil- or coal-fired electricity due to its heavy dependence on non-renewable primary energy. Incidentally, given that the largest part of the nr-CED is in the extracted uranium itself (i.e., PE in Fig. 1 [A]), this is a rather general result which is largely transferable to other countries too[6].

Natural gas-fired electricity performs well in terms of NTG, and, when of the modern combined cycle type, it is also marginally more sustainable (i.e., it has a lower nr-CED) than the average electricity produced by the current UK grid. It therefore appears to be the best candidate technology in order to maintain, and further expand if needed, an important reserve capacity for readily dispatchable electricity (some of which will also be required as back-up in scenarios of large-scale deployment of renewable technologies like wind and PVs).

Hydroelectricity provides far and away the best overall performance of all analysed technologies from both the NEA and LCA perspectives, as evidenced by its being positioned in the very top-right corner of the chart. However, the hydrography of the UK constitutes a major constraint, leaving comparatively little margin to scale this technology up beyond approximately 200% of its current installed capacity (British Hydropower Association (BHA), 2011).

PV technologies were found to hold potential for remarkable performance, especially considering the country's comparatively low average irradiation. However, of the two analysed PV technologies, CdTe is the only one whose NTG is higher than that of the UK grid as a whole (its nr-CED is also lower than that of mc-Si PV). It would therefore seem advisable to push for a more widespread deployment of this comparatively novel and under-utilised technology in the future.

Last but not least, wind electricity, both on and off-shore, was found to hold the greatest all-round potential to contribute to a 'better' UK grid in the future, from both points of view of a very high NTG (higher than that of gas combined cycles, and almost as high as that of nuclear) *and* of the second-lowest nr-CED of the entire set of analysed technologies.

5. Conclusions and policy implications

The body of work presented herein represents, to the best of our knowledge, the first complete and fully consistent assessment of the actual all-round energy performance of the full range of electricity generation technologies currently deployed in a specific country, taking into account both their short-term *effectiveness* at providing a NEG for the benefit of the multiple societal energy consumption patterns, and their potential long-term *energy sustainability* (the latter being inversely proportional to the reliance on non-renewable primary energy sources).

Of course, while the NEA and LCA energy performance indicators discussed in this paper are important, they should not be the sole basis for policy decision-making. As already mentioned in the introduction, issues of economic affordability, technical integration of different technologies into a single grid, energy storage, demand-side management, and of course the overarching need to significantly curb greenhouse gas emissions, all need to be taken into account.

However, our analysis still has profound policy implications, in that it identifies those technologies which, by virtue of their intrinsic *energy performance*, hold the greatest potential to enable a much-needed transition to a more sustainable national electricity mix that is less reliant on non-renewable PES, while at the same time warning against the false hopes represented by those technologies (like biomass-fired electricity) whose large-scale deployment would likely result in a worrisome reduction of the grid's overall NTG.

In particular, our new results have shown that, when compared to other electricity generation technologies in a methodologically consistent manner, the net energy returns currently afforded by conventional oil- and coal-fired electricity in the UK are much lower than what might have been expected based on the general indications provided in the pre-existing literature, and in fact lower than that of the UK grid mix as a whole. This is a very important finding that should not be lost in pursuit of other goals, however important the latter may be.

Specifically, carbon capture and storage (CCS) is often seen as a promising strategy to 'de-carbonize' coal-fired electricity and thus make it more environmentally sound (World Coal Institute, 2005; International Energy Agency (IEA), 2013), and as such it features prominently in the two most 'advanced' energy scenarios for the UK drafted by National Grid (*cf.* Table 2). CCS was not explicitly included in our analysis, since it has not been deployed anywhere yet in the UK; however, even discounting the issue of identifying sufficient suitable storage capacity (Directive, 2009/31/EC; Viebahn et al., 2012; Shogenova et al., 2014), it is clear that retrofitting CCS to existing power plants would inevitably entail an additional energy investment per unit of delivered electricity, as well as reduced available power output ("No magic fix for carbon", 2014; Sahu et al., 2014; An et al., 2015). As a result, while CCS may have a role to play in reducing GHG emissions from existing thermal power plants in the short- to medium-term, the associated increase in nr-CED and reduction in NTG would actually turn coal-fired electricity into an even less desirable electricity supply option than it is today, from the point of view of its actual *energy* performance.

Also, given how close even modern gas combined cycles are to the nr-CED threshold set by the current average performance of the UK grid mix, the benefits afforded by CCS in terms of reduced carbon intensity of gas-fired electricity (*cf.* the proposed deployment of gas CCS in Table 2) should be weighed with the utmost care against the additional demand for non-renewable energy investment.

On a more positive note, our results point to wind electricity (both on shore and off-shore) as the most recommendable option overall to enable a transition to an improved UK grid, from both points of view of a higher NTG ratio and a drastically reduced dependency on non-renewable PES. It is thus reassuring to note that all existing grid development scenarios (with the only exception of the rather pessimistic one aptly labelled "no progression" – *cf.* Table 2) do in fact rely on wind to provide the largest share of electricity supply by 2035. However, the rationale behind reduced wind deployment in favour of nuclear in the "low carbon life" scenario appears to be questionable. In fact, while both technologies are reportedly broadly equivalent in terms of their carbon intensities (Dolan and Heath, 2012; Warner and Heath, 2012), Fig. 6 makes it apparent that wind is clearly the Pareto optimal technology amongst the two, given that its nr-CED is almost two orders of magnitude lower than that of nuclear, whereas the respective NTGs are essentially the same.

Finally, one aspect in which renewables (such as wind and PV) and nuclear are clearly different is of course that of intermittency. However, as mentioned before, it is actually interesting to note that neither technology is in fact readily dispatchable (albeit for

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[6] One possible way to extend the 'renewability' of nuclear energy might be the use of 'breeder' reactors capable of generating more fissile material than they consume by either using 'fast' (unmoderated) neutrons to breed fissile Pu (and possibly higher trans-uranic elements from ^{238}U), or using thermal spectrum (moderated) neutrons to breed fissile ^{233}U from Th. However, none of the extant nuclear reactors in the UK, nor any of those planned for the foreseeable future, are of the breeder type.

opposite reasons), and therefore neither would be able to single-handedly follow the dynamic pattern of societal electricity demand. The potential impact of energy storage will thus have to be carefully assessed in future research – but critically, as part of a fully-fledged prospective analysis of the energy performance of the whole grid under a number of alternative development scenarios, rather than as part and parcel of any individual technologies in isolation (Carbajales-Dale et al., 2015).

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Appendix A. Supplementary material

Supplementary data associated with this article can be found in the online version at http://dx.doi.org/10.1016/j.enpol.2015.12.011.

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