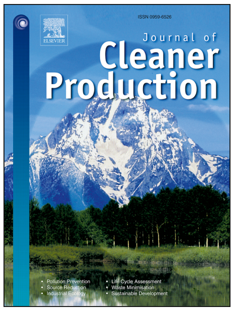

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# Can Electric Vehicles significantly reduce our dependence on non-renewable energy? Scenarios of compact vehicles in the UK as a case in point.

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## Abstract

Electric vehicles (EVs) are increasingly regarded as the way forward to deliver a much-needed improvement in the transport sector's sustainability profile, and the UK is embarking on a major transition towards them. While previous studies focused mainly on greenhouse gas (GHG) emissions, this article assesses the extent to which EVs may contribute to reducing the UK's dependence on (mostly imported) non-renewable primary energy. The study combines a life-cycle model of a compact battery electric vehicle (BEV) with a prospective energy analysis of a range of electricity supply alternatives for the vehicle's use phase. The key metric analysed is the non-renewable cumulative energy demand (nr-CED). Results show that, already under current conditions, the nr-CED of a compact BEV in the UK is lower by approximately 34% with respect to that of an otherwise similar internal combustion engine vehicle (ICEV). Such reduction is then expected to improve further under all future scenarios, indicating that a transition to EVs is indeed a recommendable option to reduce the UK’s demand for non-renewable energy, especially if this is accompanied by a shift to a more renewable electric grid.

**Keywords** Battery electric vehicles; non-renewable cumulative energy demand; life cycle assessment; prospective analysis

## 1. Introduction

The world is witnessing the first steps of a gradual shift towards electric power trains for passenger vehicles, which are being promoted by policy-makers as a “greener” alternative to internal combustion engine vehicles (ICEVs). In the UK in particular, registrations of electric vehicles (EVs) have soared exponentially in recent years (Nextgreencar, 2017), and sales of new conventional ICE vehicles will be banned after 2040 (UK Gov, 2017). The uptake of EVs is projected to accelerate in the next two decades with concerns over local air quality as well as overall emissions (Althaus, 2012; Cuenot et al., 2012; Nilsson et al., 2016). It is therefore important to estimate the foreseeable energy and environmental consequences of this impending large-scale change, by analysing the complete life cycle of typical EVs, while considering a range of possible electricity supply mixes used to recharge the vehicles’ batteries during the use phase.

The literature that has tackled these issues has so far focused mainly on greenhouse gas (GHG) emissions. For instance, Faria et al. (2013) found that, depending on the grid supply mix of the country where they are driven, compact EVs emit between approximately -60% (France) to +16% (Poland) $CO_2$-equivalents with respect to conventional ICEVs of the same size segment. In a dynamic analysis focusing on the entire passenger vehicle fleet of Portugal, Garcia et al. (2015) found that moving from  the current fleet composed on 33% petrol ICEVs and 67% diesel ICEVs to a future scenario completely dominated by battery electric vehicles (100% BEVs in 2030), while keeping the carbon intensity of the electricity grid mix constant, would result in a 37% reduction in overall GHG emissions; the authors then performed a sensitivity analysis on the key model parameters, including the grid mix carbon intensity, leading to wide range of possible results. The dependence of an EV's overall life-cycle GHG emissions on the composition of the electricity mix used to recharge its batteries was then investigated in even more detail by McLaren et al. (2016), who based their modelling on high-resolution time series of grid carbon intensity and EV load profiles. Fernández et al. (2018) again focused their analysis on GHG emissions, but instead approached the issue from the point of view of the discrepancy between idealized test drive cycles and real-world energy consumption data. Finally, Canals Casals et al. (2016) combined some of the elements of the studies mentioned above, by looking at the combined effect of a range of drive cycle scenarios with different electricity supply mixes for a number of European countries.

The complementary issue of the vehicles' demand for non-renewable energy has received comparatively little attention in the literature, and of those relatively few studies that did look into it, most focused on vehicle fuel consumption only. As a case in point, Bradley and Frank (2009) only analysed the direct consumption of petroleum fuels by ICEVs and EVs during their use phase, acknowledging that "these petroleum reduction figures do not account for the petroleum used to generate electricity as energy from oil makes up less than 3% of the total US electrical energy". Thus, their analysis failed to take into account all the other types of non-renewable energy that are used: (i) in the other life-cycle stages of the vehicles (including extraction and processing of the raw materials for their production and maintenance), and (ii) to supply the electricity used by the EVs during their use phase (including the demand for primary energy in the forms of gas, coal and uranium).

The purpose of this article is then to fill this knowledge gap, and assess the extent to which EVs may be expected to contribute to reducing the transport sector's dependence on all forms of non-renewable energy, while accurately quantifying the relative importance of a range of factors at play. Among the latter, two stand out, namely: the higher efficiency of the electric power train (*vs.* internal combustion engines); and the composition of the grid mix supplying the electricity to the vehicles (which is expected to undergo significant changes in the decades ahead). Given that over 60% of passenger vehicle registrations in the UK are for compact vehicles (SMMT, 2018), it was decided to develop, and use as the basis for the analysis, a detailed life-cycle model that would be representative of this size segment. Inferences were then also made on the potential results for the whole fleet by means of suitable scaling factors and extrapolations. Finally, given that the vast majority of the non-renewable energy used in the UK is imported from abroad, the results are also relevant in terms of the country's overall energy independence.

## 2. Materials and Methods

### 2.1 LCA model of a compact battery electric vehicle

The chosen functional unit for the study was the cradle-to-grave (excluding end-of-life management) life cycle of a compact passenger vehicle, including an assumed 150,000 km use phase. The starting point for the analysis was a model previously co-developed with colleagues from Coventry University (UK) for the analysis of a range of possible lightweighting strategies for passenger vehicles (Raugei et al., 2015). Rather than refer to any specific production car, this model was based on a theoretically derived bill of materials (provided in the Supplementary Materials), and conceived to be largely representative of the current state of the art for a typical compact vehicle, i.e., one straddling the “Mini” and “Supermini” UK segment designations (SMMT, 2018), which are largely equivalent to the corresponding European “B” and “C” segments.

As illustrated in Figure 1, the assessment covers the following vehicle life cycle stages:

1. Sourcing of raw materials and respective manufacturing routes;
2. Vehicle manufacturing;
3. Vehicle use phase;
4. Vehicle maintenance.

**Figure 1.** Schematic illustration of the vehicle life-cycle stages considered in the analysis.

As already mentioned, End-of-life (EoL) management as well as all associated energy credits arising from the recovered materials were excluded from the present analysis. This decision was principally based on the fact that, while many options are being considered (Ordoñez et al., 2016; Raugei and Winfield, 2017; Wang and Wu, 2017; Yun et al., 2018; Glencore, 2018; Sumito, 2018; Umicore, 2018;), a mature, standardized and widely-adopted take-back and recycling scheme for Li-ion EV batteries is not yet in place. An additional consideration was that, when considering the existing EoL vehicle legislation (Directive 2000/53/EC) and the current practice in aluminium recycling (Aluminium Federation, 2013), the analysis of previous results (Raugei et al., 2015) indicates that the combined effect of the additional energy demand for EoL treatment and the ensuing energy credits, if considered, may be expected to only marginally affect the total nr-CED of the vehicles, and therefore not significantly alter the relative ranking or interpretation of the results presented here.

The modelling of life cycle stages 1, 2 and 4 (as described above) was carried out within the GaBi Professional software package (Thinkstep, 2017), as was that of stage 3 (use phase) for the reference case of a conventional internal combustion engine vehicle (ICEV). Instead, the use phase of the EV alternative, including the all-important electricity supply mix scenarios, was modelled separately, as described in Section 2.3. All background processes, including those for stage 1 (material supply chains), were sourced from the widely-employed Ecoinvent database (Ecoinvent, 2016).

The analysis of the vehicle’s main sub-assemblies, namely the body, chassis, power train, electrical system, and trim, was streamlined to a degree of granularity that was deemed sufficient to capture the essential life cycle energy performance traits of the two alternative options (ICEV *vs*. EV). In particular, the body and chassis were assumed to consist of optimized all-steel architectures, whereas advanced lightweighting alternatives using combinations of aluminium, magnesium and carbon fibre reinforced polymers were discarded as outside of the intended scope of this investigation. For more details on this part of the model, the reader is referred to the block diagram of the structural model and the foreground inventories supplied in the Supplementary Materials.

Two power train options were considered: firstly, one based on a 44kW ICE to provide a frame of reference, and then one using an electric motor of equivalent power. The electrical systems were also adapted to the respective power train alternatives, and included a conventional lead-acid battery for the ICEV, and a 24 kWh Li-ion battery pack for the battery electric vehicle (BEV). In particular, the latter battery pack was modelled on the basis of the relevant processes available in Ecoinvent, assuming a lithium manganese oxide (LMO = $LiMn_2O_4$) cathode chemistry, and including all the necessary ancillaries (battery management system, cooling system, etc.).

This way of framing and modelling the comparison between the two power train alternatives essentially corresponds to assuming a retro-fit conversion of a conventional ICEV to a functionally equivalent BEV version. This was deemed to be relevant as it appears to reflect the readily implementable strategy that several manufacturers are starting to adopt in order to be able to quickly introduce a first fleet of BEVs to the market (Volkswagen 2017; Ford, 2017).

In both cases, scheduled maintenance over the assumed 150,000 km lifetime of the vehicle included multiple tyre, lubricant and brake pad replacements (every 30,000 km), one full battery replacement, and 10% outer body panel replacement (due to impact damage). It is worth mentioning that, on the one hand, the assumption of one Li-ion battery pack replacement mid-way through the expected service lifetime of the vehicle may be considered a conservative one for state-of-the-art BEVs, since some manufacturers have started to give warranties of up to 160,000 km or 8 years on the originally installed battery pack (Nissan, 2017). On the other hand, however, the possible future widespread adoption of fast charging stations may marginally reduce the service life of the battery packs due to accelerated cell degradation (Neubauer and Wood, 2015).

For the ICEV, the use phase fuel consumption was assumed to be equal to the officially claimed figure for the 1.2L Volkswagen Polo mk4 (the latter chosen as having approximately the same kerb mass and engine power as the idealized model vehicle), i.e., 6.0 L (petrol) per 100 km under New European Driving Cycle (NEDC) conditions. The energy consumption of the BEV was assumed to be 15 kWh (electricity) per 100 km under NEDC conditions, which coincides with the officially claimed figure for the Nissan Leaf (Nissan, 2017), which is the fastest-growing C-segment car in the UK (Nissan, 2016); the same value also sits in the middle of the range recently reported for a number of compact EVs under the same NEDC conditions (Grunditz, 2017). While such NEDC energy consumption estimates might be regarded as somewhat optimistic in absolute terms (by as much as 21% according to one study (Mock et al., 2012)), it was considered that they would still be suitable for the purposes of allowing a balanced comparison between the two power train alternatives.

Finally, the life cycle impact metric of choice to assess the vehicles' dependence on non-renewable primary energy over their full life cycle was the non-renewable cumulative energy demand (nr-CED). This metric measures the total non-renewable primary energy that is harvested from the environment, thereby including all direct and indirect energy inputs that are traceable back to petroleum, natural gas, coal and uranium reserves (Hischier et al., 2010; Frischknecht et al., 2015a). In particular, cumulative fossil fuel use is quantified on the basis of the higher heating value (HHV) of the primary resources in the ground, and cumulative uranium use is quantified on the basis of the nuclear fuel supply chain as modelled in Ecoinvent, i.e. using data for an average pressurized water reactor

(PWR). The latter does not include the energy content in the depleted uranium from the enrichment process, and may therefore be regarded as a lower-bound 'optimistic' value.

## 2.2 First-order extrapolation to entire UK passenger vehicle fleet

In order to allow the estimation of the nr-CED of an average passenger vehicle that could be considered representative of the entire UK fleet (as opposed to the "Mini" and "Supermini" segments only), its kerb mass and fuel (for the ICEV variant) or electricity (for the BEV variant) consumption were extrapolated on the basis of the weighted average values for each segment type. The latter figures were sourced from the available literature on the most popular cars for each segment in the UK (SMMT, 2018), and then rounded off to two significant digits. The results of such extrapolations are reported in Table 1. All other assumptions (lifetime, maintenance, etc.) remain the same as those detailed in Section 2.1 for the compact vehicle.

**– Table 1 here –**

The calculation of such average vehicle's nr-CED was then based on the first-order assumption that the shares thereof corresponding to life cycle stages 1,2 and 4 (raw materials, manufacturing and maintenance) would be directly proportional to the vehicle's kerb mass, while the share corresponding to the use phase (stage 3) would be directly proportional to the vehicle's fuel (or electricity) consumption. While admittedly somewhat crude, these assumptions were deemed robust enough for the purpose of double-checking whether the accurately determined results for the analysed compact vehicle would fundamentally remain applicable to the UK passenger vehicle fleet as a whole, at least in terms of the relative order of preference for the different scenarios (described in Section 2.3 hereinafter).

## 2.3 Electricity supply scenarios for the BEV use phase

The life-cycle energy performance of an EV during its use phase is of course heavily dependent on the specific system that supplies the electricity used to recharge the on-board Li-ion batteries. In order to properly take this into account, and to perform a sensitivity analysis to investigate a range of alternative scenarios, an original model of the UK electricity grid was used. This model was co-developed with colleagues from the University of Manchester (UK), and a detailed description of it has been provided in three previous papers (Raugei and Leccisi, 2016; Jones et al., 2017; Raugei et al., 2018). At its core, the model relies on a quantitative definition of the amounts of installed power for all electricity generation technologies that comprise a given grid mix, then calculates the amount of electricity produced by each technology using an original unit commitment model (Zhang et a., 2016), and finally produces a range of life-cycle metrics for the combined grid mix (also taking into account all grid infrastructure and associated transmission and distribution losses), among which the nr-CED which is of interest here.

All the underlying background processes for the modelling of the individual technologies were based on the corresponding Ecoinvent processes, but individually amended and adapted so as to better represent the actual technologies expected to be in use in the UK at the time of analysis (UK Gov BEIS, 2016; 2017). In particular:

- Coal supply in 2016 was modelled as being imported, mainly from Russia, the USA and Colombia, and burned in power plants at 34% efficiency.

- Natural gas supply in 2016 was modelled as being 50% domestic and 50% imported (mostly from Norway), and burned in combined cycle power plants at 47% efficiency. Since CCGTs are a mature technology, their efficiency was assumed to remain the same in the future too. However, by 2035, a share of installed capacity was assumed to be fitted with carbon capture and sequestration (CCS) technology, which has been estimated to increase the feedstock demand by 11-22% (IPCC, 2005); hence, the conversion efficiency of CCS-CCGTs was assumed to be reduced to 40.5% on average.
- Nuclear fuel supply was assumed to be sourced from the same mix of countries as for the EU as a whole, i.e., mostly from Kazakhstan, Canada, Russia, Nigeria and Australia (European Commission, 2014), because UK-specific information in this regard is not made available by the UK government. Centrifuge uranium enrichment was assumed throughout, since this has supplanted diffusion enrichment to become the most widely employed method worldwide (World Nuclear Association, 2015), and all power plants were then modelled as pressurized water reactors (PWR), because this was the technology for which the most complete life cycle inventory data were available. It is noteworthy that while at present most nuclear power stations in the UK use advanced gas-cooled reactors (which are technically similar to PWRs, but somewhat more complex), all new power plants planned for the future deployment are expected to be of the PWR type (NAMRC, 2015).
- Biomass feedstocks to UK power plants was modelled as comprising a mix of pellets (imported from North America), and wood chips and straw (both domestically sourced). The power plant conversion efficiency was kept at the reported value of 24% throughout.

- Hydroelectric power plants were modelled as 87% reservoir and 13% run-of-river, and expected to have a useful service life of 80 years.
- Wind power plants were modelled as approximately 50% on shore and 50% off-shore in 2016, and 1/3 on shore and 2/3 off-shore in 2035. A service life of 20 years was assumed for the moving parts and the off-shore fixed parts, and 40 years for the on shore fixed parts.
- Photovoltaic (PV) installations were modelled as multi-crystalline silicon (mc-Si), which is by far the most widely deployed technology worldwide (Fraunhofer ISE, 2016); 75% of the installations were assumed to be rooftop systems, consistently the results of a stakeholder consultation exercise involving National Grid and the principal involved actors in the UK (Jones et al., 2014). Given that PV systems are undergoing a rapid evolution in terms of both manufacturing and resulting module efficiency, special care was taken to employ the latest inventory data (Frischknecht et al., 2015b; Leccisi et al., 2016), and assumptions of expected future improvements (Frischknecht et al., 2015c). Specifically, module efficiency was modelled as 16% in 2016 and 23% in 2035.

A number of key input parameters for the grid mix model were then allowed to change in order to represent the four alternative electricity supply scenarios, as described below.

Baseline: This scenario, informed by the latest electricity production data published by the UK department of Business Energy and Industrial Strategy (UK Gov BEIS, 2017), is intended to represent the performance of the current UK grid mix (excluding the small share of electricity supply that comes from abroad via the interconnectors with mainland Europe).

Table 2 lists the main data pertaining to the 2016 grid mix in terms of installed power (column 2), capacity factors[1] (CF, column 3) and resulting electricity generation mix (column 4).

The CFs of thermal technologies such as coal, gas, nuclear and biomass are in principle only technically limited by the necessary down time for maintenance or by a scarcity of feedstock supply. As can be seen in Table 2, nuclear power, which is fundamentally a baseload technology intended to run at close to maximum output at all time, exhibits a CF near its theoretical maximum (78%). Combined cycle gas turbines (CCGT) are more flexible, and are also partly used as load-following power plants, thereby reducing their overall yearly average CF to 49%. The even lower (38%) CF for biomass electricity is due to the intrinsic limitations in supply for this type of feedstock, a large share of which is imported from overseas, resulting in low net energy performance (Raugei and Leccisi, 2016). Finally, the very low (17%) CF for coal generation is entirely due to this technology already being intentionally phased out at a rapid pace.

The CFs of renewable technologies such as hydro, wind and PV are instead fundamentally constrained by the availability of the renewable energy flows they feed on (respectively, rainfall, wind power and solar irradiation), and tend to fluctuate year by year depending on weather conditions. Wind and PV are additionally conditioned by the absence of any 'built-in' energy storage system, which means that the only way to control their output and adapt it to the electricity demand profile is to resort to curtailing during times of peak production, which of course negatively affects the yearly average CF.

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[1] Capacity Factors (CFs) are defined as the ratio of the average effective power output to the nominal installed power.

*Using the numbers presented in Table 2 in the analysis of the use phase of the BEV leads to an estimate of the nr-CED of operating such a BEV today.*

**- Table 2 here -**

Scenario 1: This is a prospective scenario that is intended to represent the expected performance of the UK grid mix in 2035, based on the projected installed capacities of the various electricity generation technologies in the latest Future Energy Scenarios report issued by National Grid, under their "2 degrees" scenario (National Grid, 2017). The latter is the most ambitious among the grid evolution scenarios considered in the report. It assumes that in order to meet the projected future electricity demand, while staying on track towards meeting the maximum 2 degrees increase in global temperature discussed in the recent 21st Conference of the Parties (UNFCCC COP, 2015), by 2035 it will be necessary to: have completely phased out coal use, have almost completely phased out natural gas use (and have deployed carbon capture and sequestration (CCS) on about half of the remaining CCGT capacity), and have aggressively boosted wind, and to a lesser extent PV, penetration (respectively to approximately +400% and +300% with respect to today’s installed capacity). Installed nuclear power is also assumed to increase by approximately +70% in absolute terms, thereby continuing to represent a similar relative share of the cumulative installed electricity generation capacity of the entire grid and providing most of the required baseload capacity. According to National Grid, a wide range of policy measures will be required to make this scenario possible, among which incentives to increase end-use efficiency and reduce overall electricity demand, as well as use of smart technologies to optimally manage the electricity demand profile. Specifically as regards the transport sector, this scenario assumes a rapid deployment of BEVs (up to approx. 5 million vehicles by 2030 and over 15 million ones by 2040) and a concomitant steady rise of autonomous BEVs, which are expected to eventually reach 50% of all BEVs by 2050 (National Grid, 2017). Adopting the installed capacities assumed by National Grid for the “2 degrees” scenario, and using the original unit commitment model previously developed (Zhang et a., 2016) and tested on similar future grid mix scenarios (Raugei et al., 2018), led to new CF estimates for 2035, as illustrated in Table 3 (column 3). Specifically, conventional CCGTs are assumed to be on the wane (hence the low CF) and to be replaced by CCS-CCGTs, which will be used more intensively as low-carbon baseload providers (hence the higher CF *vs*. that for CCGT in Table 2). Biomass use is also expected to be ramped up (inevitably requiring more imports), while the CF of wind is expected to be reduced to 24% because of the need to curtail some peak production. The CF of PV is not affected because wind is assumed to be preferentially curtailed with respect to PV.

*Adopting the numbers presented in Table 3 for the use phase of the BEV leads to an estimate of the nr-CED of operating such a BEV in 2035, under the assumption that it will be possible to meet the additional demand for electricity posed by EVs using the same balanced mix of technologies that, on average, supply electricity for all other uses in the country*.

**- Table 3 here -**

<u>Scenario 2</u>: This is a simple first-order approximation scenario in which all of the electricity required to recharge the EV batteries comes from conventional CCGTs. *The rationale for analysing this scenario is that CCGTs are currently the most readily dispatchable technology that could be used in the near term to meet a sudden surge in demand caused by an early large-scale uptake of EVs.* This particular investigation follows a similar logic (albeit to a

lower level of detail) as that of a previous literature study on the consequences of marginal electricity supply for EVs in Portugal (Garcia and Freire, 2016).

Scenario 3: Finally, this third future scenario is intended to investigate the opposite end of the spectrum, i.e., the case in which all of the electricity required to recharge the EV batteries comes from renewable resources, and specifically a combination of 85% wind and 15% PV generation. *This scenario is intended to reflect the case in which, in the long term, optimal demand-side management would enable a sub-fleet of EVs to be recharged almost exclusively during times of peak renewable electricity production, thereby reducing or even avoiding the otherwise projected need to curtail excess production.*

## 3. Results and discussion

Table 4 first presents the results of the analysis of the four electricity supply scenarios discussed in Section 2.3 in terms of their nr-CED.

**- Table 4 here -**

Figure 2 illustrates the results of the complete LCA of the analysed compact BEV under the four electricity supply scenarios considered, benchmarked against the functionally equivalent vehicle equipped with a conventional ICE power train. Figure 3 then presents the same results, but for an average passenger vehicle representative of the entire UK fleet, based on the first-order extrapolations discussed in Section 2.2.

**Figure 2.** Life-cycle non-renewable cumulative energy demand (nr-CED) of the analysed compact passenger vehicle, respectively when using an internal combustion engine (ICEV),

and an equivalent battery electric power train (BEV), the latter under four alternative electricity supply scenarios.

**Figure 3.** Life-cycle non-renewable cumulative energy demand (nr-CED) of an average passenger vehicle representative of the entire UK fleet, respectively when using an internal combustion engine (ICEV), and an equivalent battery electric power train (BEV), the latter under four alternative electricity supply scenarios.

First, it is interesting to note how, even under current (Baseline) conditions, the life-cycle nr-CED of a BEV is already significantly lower (-34% for the compact vehicle analysed in detail, and -36% for the extrapolation to the average vehicle representative of the whole fleet), with respect to that of an otherwise similar vehicle powered by a conventional internal combustion engine (ICE). Also, by way of a simple sensitivity analysis performed on the compact vehicle, even if its use-phase electricity consumption were significantly higher at 20kWh/100km (i.e., at the very top of the range reported in the literature (Grunditz, 2017)), its life-cycle nr-CED would still be 20% lower than that of the compact ICEV. This is a reassuring finding, which points to the fact that the on-going drive towards a progressive electrification of the UK passenger vehicle fleet is indeed well-guided.

The shift to an aggressively de-carbonized grid mix such as that projected by National Grid under their “2 degrees” scenario (corresponding to Scenario 1 here) could then further reduce the vehicle’s dependence on non-renewable energy, bringing its life-cycle nr-CED down to almost one half of that of the conventional ICEV (this applies both to the analysed compact vehicle, and to the average fleet). However, it is also noteworthy that such a future grid mix is expected to rely heavily on nuclear (and to a lesser extent on CCS-CCGTs) as baseload providers of electricity, and that while these are unquestionably low-carbon technologies, they are still based on the thermal (and hence inherently inefficient) exploitation of non-renewable primary energy resources (respectively uranium ore and natural gas). This continued dependence on non-renewable resources ultimately constrains the achievable further reductions in the nr-CED of the grid mix electricity (Table 4) and consequently also that of BEVs that feed on such mix. Also, as discussed in Section 2.3, reaching the results presented for scenario 1 will not be easy, as the grid will have to rely on the deployment of smart technologies (including demand-side management) in order to cope with the additional demand placed by the whole EV fleet. On the other hand, if autonomous driving does become more common in the future, the use-phase electricity demand of the drive train per km travelled may come down thanks to smoother flowing traffic requiring less acceleration and braking, which may in and of itself further reduce the life-cycle nr-CED of the BEV.

Analysis of Scenario 2 highlights how a very rapid EV uptake that would initially require more CCGTs to be used as readily dispatchable marginal electricity producers, could result in a slightly worse performance in terms of nr-CED *vs*. that of a BEV powered by the current grid mix. However, overall this potential temporary dip in performance should not be the cause of too much concern, as even under these relatively unfavourable conditions, the nr-CED of a BEV would still be approximately two thirds of that of a conventional ICE equivalent (once again, this applies both to the compact vehicle and to the extrapolation to the average vehicle for the entire UK fleet). This remarkable result is clearly indicative of the fact that adopting more efficient electric power trains for passenger vehicles is intrinsically beneficial, and potentially conducive to a significantly reduced overall dependency on non-renewable energy resources, even when the source of the electricity used to recharge the vehicle's batteries is ultimately 100% non-renewable itself. In fact, a large part of this improvement is due to the combined higher efficiency of: (i) the electric motor (which typically runs at 80-95% efficiency), plus (ii) the EV charging efficiency (approximately 90%), plus (iii) the CCGT power plant conversion efficiency (47%), plus (iv) the natural gas supply chain efficiency (96% from primary resource to gas delivered to the power plant), *vs*. (i) the ICE (which is at best approximately 30-35% efficient when running at optimal RPMs and 0% efficient when idling), plus (ii) the petrol supply chain efficiency (approx. 81% from crude oil to petrol delivered to the pump).

Finally, the analysis of Scenario 3 highlights the very significant extent by which a BEV's dependence on non-renewable energy resources could be reduced (i.e., over -70% *vs*. the corresponding ICE alternative) if the electricity to recharge its batteries could be sourced entirely from excess wind and PV generation. Even if achieving such results for the entire fleet will likely remain utopian for the UK, optimal deployment of smart technologies and widespread user engagement could conceivably make this a reality for at least a sub-fleet of BEVs in the medium-to-long term. Additionally, it is worth mentioning that the results produced under Scenario 3 may also be deemed indicative of the non-renewable cumulative energy performance of EVs today in countries where the electricity grid mix is already characterized by a large preponderance of renewable energy technologies, like e.g., Norway: 98% renewable (Norwegian Government, 2017) and Iceland: 100% renewable (Askja Energy, 2017).

## 4. Conclusions

This detailed analysis has shown that the potential benefits of fleet electrification, in terms of life-cycle non-renewable energy demand, could be very significant.

One first fundamental factor at play in reducing the dependency on non-renewable energy was ascertained to be the intrinsically higher efficiency of the electric power train, as highlighted by the fact that even when the electricity used to recharge the EV’s batteries was modelled as being entirely generated by combined cycle gas turbines (and therefore 100% non-renewable), the resulting nr-CED over the vehicle’s life cycle was still approximately 32% lower than for a similar conventional ICEV. This result is doubly important, as it also points to the fact that the larger demands for non-renewable energy in the other stages of an EV’s life cycle (specifically manufacturing and maintenance) *vs*. those of a conventional ICEV are not enough to offset the reduced demand in the use phase.

Incidentally, a comparison to the results of a previous investigation (Raugei et al., 2015) also indicates that the transition to electric power trains holds the potential to be a far more effective strategy to this end than lightweighting conventional ICEVs.

The results produced under Scenarios 1 and 3 then point to the electricity supply mix as the second most important factor in potentially achieving even larger reductions in the demand for non-renewable primary energy over the life cycle of an ever-more electrified fleet of passenger vehicles.

However, the ultimate extent of the achievable improvements in terms of reduced demand for non-renewable energy resources in the UK will depend on a number of technical and behavioural factors. Among the former are: (i) the rate of EV deployment *vs*. the rate and extent of change in the grid mix composition; and (ii) the establishment of an effective demand-side management scheme (using appropriate regulation, 'smart' meters, economic incentives, etc.). In terms of behavioural factors, it is then important to mention that, from a quantitative point of view, improvements in the energy efficiency of energy-using products (such as vehicles) do not always necessarily result in parallel reductions in the total demand for energy resources. This somewhat counterintuitive outcome, first postulated by Jevons (1865) and since aptly referred to as Jevon's paradox, is due to the possible onset of increased use of the product by consumers at large, and it has been well documented and discussed at length in the literature (Sorrell, 2009; Madureira, 2014; Giampietro and Mayumi, 2018). Additionally, it is also noteworthy that the expected reliance on nuclear power in National Grid's "2 degrees" future grid mix scenario would place a hard limit on what may be achievable in terms of non-renewable cumulative energy demand (nr-CED). Instead, an even larger deployment of wind and PV technologies, coupled with enhanced use of smart technologies and active user engagement to foster vehicle recharging at times of peak renewable electricity generation and reduce the need for renewable energy curtailment, could potentially open the door to the highest reductions in the nr-CED of battery electric vehicles, and hence the UK's overall dependence on non-renewable energy.

Finally, there remains scope for future research to investigate the large-scale consequences of the co-evolution of the passenger vehicle fleet and the electricity grid in terms of the joint overall demand for non-renewable primary energy, when also taking into account a number of additional system-level variables. Among these are the possible gradual transition from the conventional transport model based on direct vehicle ownership to one in which the accent is shifted to the provision of transportation services (measured in person-kilometres), and the possible synergies offered by vehicle-to-grid and second-life EV battery storage to allow increased penetration of renewable technologies in the electricity grid.

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| Segment | Mini | Supermini + Lower Medium | Upper Medium | Executive + Luxury | Sports | Dual + Multi Purpose |
|---|---|---|---|---|---|---|
| Registrations in 2017 | 76616 | 1607761 | 256924 | 138304 | 49774 | 563407 |
| Market share | 3% | 60% | 10% | 5% | 2% | 21% |
| Segment average kerb mass [kg] | 950 | 1168 | 1600 | 1800 | 1400 | 1800 |
| Segment average fuel cons. (ICEV) [L/100km] | 4.5 | 6 | 9 | 14 | 10 | 11 |
| Segment average electricity cons. (BEV) [kWh/100km] | 11.3 | 15 | 22.5 | 35 | 25 | 27.5 |
| Fleet average kerb mass [kg] | 1372 | | | | | |
| Fleet average fuel cons. (ICEV) [L/100km] | 8 | | | | | |
| Fleet average electricity cons. (BEV) [kWh/100km] | 19 | | | | | |

Table 1. Composition of the UK passenger vehicle fleet by segment, assumptions on segment-average kerb mass and fuel/electricity consumption, and extrapolations to fleet average values.

| Technology | % installed power | % CF | % generated electricity |
|---|---|---|---|
| Coal | 15% | 17% | 7% |
| Gas (CCGT) | 35% | 49% | 46% |
| Nuclear | 11% | 78% | 22% |
| Biomass | 6% | 38% | 6% |
| Hydro | 2% | 34% | 2% |
| Wind | 18% | 29% | 14% |
| PV | 13% | 8% | 3% |

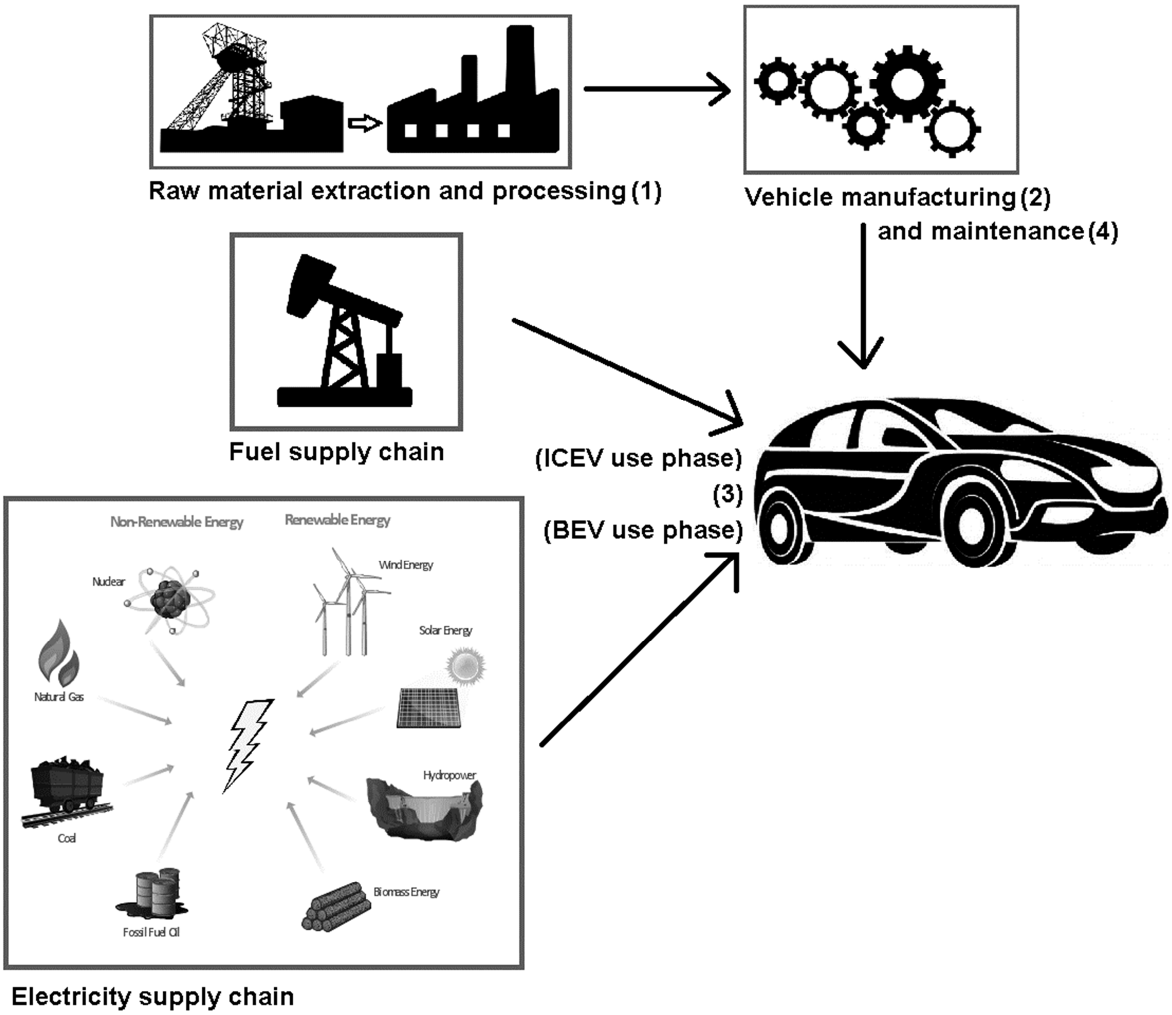
Table 2. Main parameters of the UK electricity generation grid mix in 2016 (CCGT = Combined Cycle Gas Turbine; PV = PhotoVoltaic). Capacity Factor (CF) is defined as the ratio of the average effective power output to the nominal installed power.

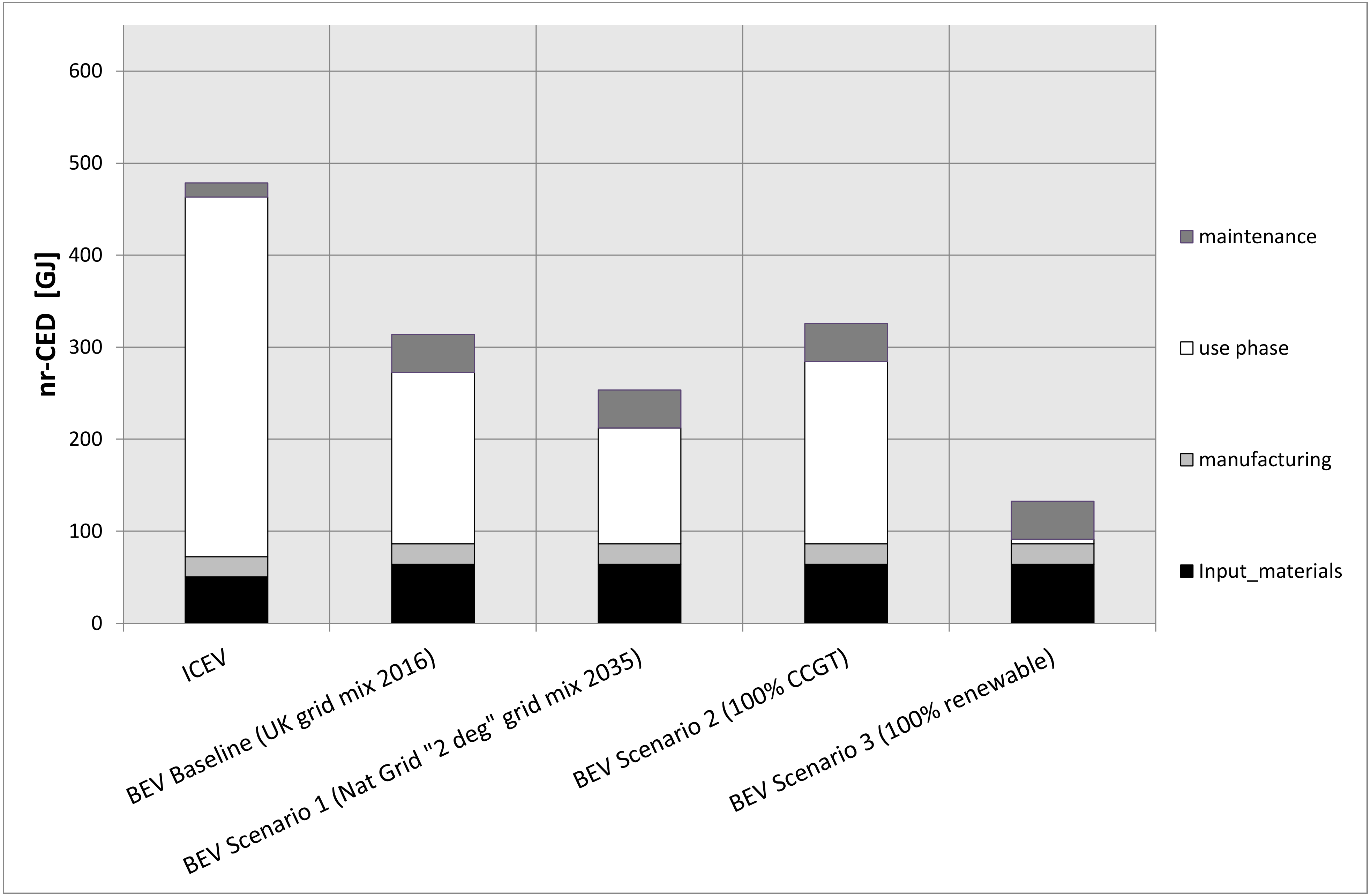
| Technology | % installed power | % CF | % generated electricity |
|---|---|---|---|
| Coal | - | - | - |
| Gas (CCGT) | 2% | 15% | 1% |
| CCS Gas (CCGT) | 2% | 67% | 5.5% |
| Nuclear | 12% | 79% | 33% |
| Biomass | 5% | 45% | 8% |
| Hydro | 2% | 35% | 2% |
| Wind | 51% | 24% | 43% |
| PV | 26% | 8% | 7.5% |

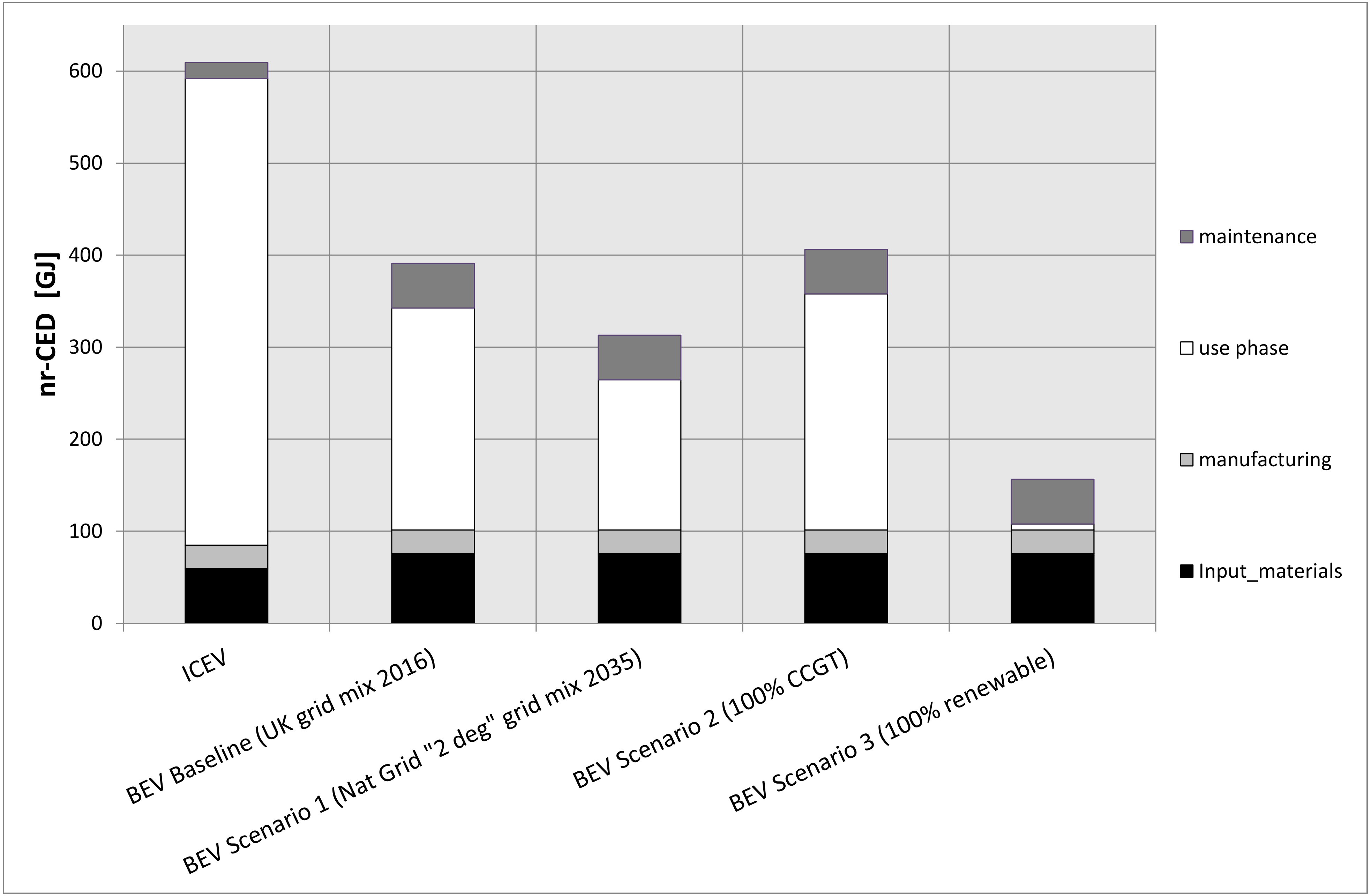
Table 3. Main parameters of the projected UK electricity generation grid mix in 2035, according to National Grid's "2 degrees" scenario. (CCGT = Combined Cycle Gas Turbine; CCS = Carbon Capture and Sequestration; PV = PhotoVoltaic). Capacity Factor (CF) is defined as the ratio of the average effective power output to the nominal installed power.

| Scenario | nr-CED<br>[MJ (nr-PE) / kWh (electricity)] |
|---|---|
| Baseline (UK grid mix 2016) | 7.5 |
| Scenario 1 (Nat Grid “2 deg” UK grid mix 2035) | 5.0 |
| Scenario 2 (100% CCGT) | 7.9 |
| Scenario 3 (100% renewable: 85% Wind + 15% PV) | 0.2 |

Table 4. Non-renewable cumulative energy demand (nr-CED) of four alternative electricity supply options for the use phase of BEVs.


Raw material extraction and processing (1)
Vehicle manufacturing (2)
and maintenance (4)
Fuel supply chain
(ICEV use phase)
(3)
(BEV use phase)
Non-Renewable Energy
Renewable Energy
Nuclear
Wind Energy
Solar Energy
Natural Gas
Hydropower
Coal
Biomass Energy
Fossil Fuel Oil
Electricity supply chain


nr-CED [GJ]
600
500
400
300
200
100
0
ICEV
BEV Baseline (UK grid mix 2016)
BEV Scenario 1 (Nat Grid "2 deg" grid mix 2035)
BEV Scenario 2 (100% CCGT)
BEV Scenario 3 (100% renewable)
maintenance
use phase
manufacturing
Input_materials


nr-CED [GJ]
0
100
200
300
400
500
600
ICEV
BEV Baseline (UK grid mix 2016)
BEV Scenario 1 (Nat Grid "2 deg" grid mix 2035)
BEV Scenario 2 (100% CCGT)
BEV Scenario 3 (100% renewable)
maintenance
use phase
manufacturing
Input_materials