Cerulogy

Efficient energy

The relative efficiency of renewable energy use in vehicles with different drivetrains

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1. Context

The world is in the process of a profound energy transition to decarbonised sources of energy. A major part of that transition is expected to be based around the replacement of internal combustion engine vehicles with electric drive vehicles, powered with some combination of batteries, overhead wires and hydrogen fuel cells. Europe is at the forefront of this transition in the transport sector.

While the direction of travel for Europe is clear, the details of the transition are still up for debate. European policy makers must consider the relative merits of a range of medium- and long-term technology options, and must build a policy environment that is fit to deliver an efficient transition. This requires balancing the drive to vehicle electrification with delivering continued progress in improving the efficiency of combustion engine vehicles, balancing the desire to increase the supply of alternative fuels against the sustainability issues associated with expanding biofuel consumption, and considering the appropriate role of emerging technologies such as electrofuels (hydrocarbon fuels synthesised with hydrogen produced by electrolysis). Across the board, it also means weighing the value of deliverable short-term changes against the need to focus on technologies with real long-term scalability.

One question for policy makers to resolve is how to appropriately balance the support given to the use of different forms of renewable energy in transport. These include renewable electricity supplied to battery electric vehicles, renewable hydrogen supplied to fuel cell vehicles, and biofuels or electrofuels supplied to internal combustion engine vehicles. The relative support available may be quite different depending on whether policies seek to give credit based on the amount of transport work that can be done, the amount of greenhouse gas emissions that can be avoided or on the amount of renewable energy supplied. Crediting electricity supplied to electric vehicles on the basis solely of the amount of energy supplied would fail to account for the greater distances that can be travelled for a single unit of energy by an electric vehicle.

The way that these questions are handled under the EU's Renewable Energy Directive (RED) has evolved several times since the first RED was adopted in 2009 (European Union, 2009). In the first RED, setting goals for 2020, the greater efficiency of electric road vehicles was recognised by counting renewable energy used by them two and a half times in assessing compliance with renewable energy targets. In 2015 this was amended by the "ILUC Directive" (European Union, 2015), which increased the multiplier for renewable electricity used in electric road vehicles to five. The recast of the Renewable Energy Directive to extend it for the period to 2030 (European Union, 2018) adjusted this multiplier again, stating that renewable electricity supplied to electric vehicles should be counted four times in assessing compliance with targets.

At the time of writing, a fourth iteration of the RED is under discussion with proposed amendments to the 2030 framework having been made as part of the Fit for 55 package (European Commission, 2021b). Under this proposal, the treatment of transport renewable energy under the RED would be moved from crediting per unit of energy to crediting per unit of greenhouse gas (GHG) emissions avoidance. Avoidance is calculated by comparison to a fossil fuel comparator GHG emissions value. This change in units implies that a new approach is needed to recognise more efficient vehicles. In the draft proposal, this would be accomplished by using a higher comparator value in assessing the contribution from electricity used in electric vehicles than in assessing the contribution from biofuels etc. This proposal may, however, be amended before a final version is agreed between the European institutions.

In this short report we review the efficiency with which renewable energy (electricity and biomass) could be utilised to deliver transport services and discuss how the latest incarnation of the RED might appropriately recognise the differing efficiency of different drivetrains.

2. Powertrain efficiency

The main underlying reason for the switch from combustion engine vehicles to electric vehicles is that greater efficiency of the electric drivetrain. It is simply possible to move a vehicle further with one megajoule of energy supplied to an electric motor than with one megajoule of petrol supplied to a combustion engine. The precise difference in energy efficiency depends on the type of vehicle and the way it is used – the efficiency advantage of electrification is eroded, for example, in the case of heavy vehicles moving large distances that would need to carry very large batteries. In this section we present 'energy economy ratios' (EERs) for a range of vehicle types. EERs are calculated by taking the ratio of energy use by a chosen reference vehicle to the energy use of the vehicle of interest[1].

2.1. JEC Tank-to-Wheels

The JEC is a consortium of the European Commission's Joint Research Centre (JRC), the European Council for Automotive Research and Development (EUCAR) and Concawe, which is the scientific division of the European Petroleum Refiners Association. Every few years the JEC publishes its 'Well-to-Wheels' (WtW) study, a review of the energy efficiency and greenhouse gas intensity of transport systems in the European Union. The Well-to-Wheels study is itself divided into two parts – Well-to-Tank (WTT) and Tank-to-Wheels (TTW). The Well-to-Tank part of the study considers the supply of energy to vehicles, while the Tank-to-Wheels part of the study considers the efficiency of energy use by the vehicles themselves.

The latest version of the JEC WTW study, version 5 (Prussi et al., 2020)[2], includes typical energy efficiency data for both passenger and medium/heavy duty vehicles, considering a range of drivetrain configurations for 'current' vehicles[3] and future vehicles[4]. Below, EER results are presented based on comparing each vehicle type to a conventional combustion engine vehicle of the same type and generation. For passenger cars, the reference is a spark ignition vehicle using E10 fuel. For medium and heavy-duty trucks the reference is a compression ignition vehicle using B7 fuel.[5]

For passenger vehicles, there is a difference in the test cycle used for the assessment between the current and future vehicles. Current vehicles are assessed based on the older NEDC (New European Driving Cycle), whereas future vehicles are assessed based on the newer WLTP (Worldwide Harmonized Light Vehicles Test Procedure). The WLTP is designed to produce results that are more characteristic of real-world driving conditions and to reduce the scope for manufacturers to optimise vehicles to achieve better test results (Dornoff et al., 2020). Differences in reported energy use between the current and future passenger vehicles therefore reflect a combination of real changes in vehicle technology and the effects of the

1 This means that be definition the EER of the reference vehicle is always 1.

2 The JEC WTW v5 consists of a number of documents and spreadsheets. When we refer to JEC WTW v5, we include this full collection, not only the 'main' report.

3 2015 models for passenger cars, 2016 for medium/heavy duty trucks.

4 Expected energy efficiency for vehicles sold in 2025

5 Note that the WTW report also includes results for 0% and 100% biofuel blends – the precise biofuel content does not affect the results at the level of precision reported.

changed test cycle. This is discussed in more detail in the passenger vehicles TTW report. In the results presented below, the EERs are always calculated by comparing a given vehicle to a reference vehicle of the same generation on the same test cycle.

The EERs calculated from the JEC WTW v5 data are shown in Table 1 for passenger vehicles and in Table 2 for medium and heavy-duty trucks. EERs for electric vehicles include energy losses associated with battery charging.

Table 1. Calculated EERs for passenger cars

Vehicle generation	Type	Powertrain	EER
2015	**Spark ignition**	Petrol engine	*1.0*
		Hybrid petrol	*1.4*
		Plug-in hybrid petrol	*2.1*
	Compression ignition	Diesel engine	*1.2*
		Hybrid diesel	*1.5*
		Plug-in hybrid diesel	*2.2*
	Electric	Battery electric (150 km range)	*3.8*
	Fuel cell	Fuel cell	*2.5*
2025	**Spark ignition**	Petrol engine	*1.0*
		Hybrid petrol	*1.4*
		Plug-in hybrid petrol	*2.4*
	Compression ignition	Diesel engine	*1.1*
		Hybrid diesel	*1.3*
		Plug-in hybrid diesel	*2.3*
	Electric	Battery electric (200 km range)	*3.3*
		Battery electric (400 km range)	*3.1*
	Fuel cell	Fuel cell	*2.0*

Source: JEC WTW v5

For passenger vehicles notice that the EERs for electric vehicles are higher in 2015 than in the predictions for 2025. This is because there is greater scope to increase the efficiency of internal combustion engines over time and therefore the efficiency differential is expected to reduce over time. Nevertheless, we see that the electric powertrain has a considerable efficiency advantage over the combustion engine, with EERs above 3 in all cases. Fuel cell vehicles also have a high EER (2 for 2025 models and 2.5 for 2015).

Table 2. Calculated EERs for medium- and heavy-duty vehicles

Vehicle generation	Type	Powertrain	EER
2016	**Long haul**	Diesel engine	*1.0*
		Hybrid diesel	*1.1*
		Battery electric	*1.7*
		Catenary electric	*2.1*
		Fuel cell	*1.3*
	Regional delivery	Diesel engine	*1.0*
		Hybrid diesel	*1.1*
		Battery electric	*2.1*
		Catenary electric	*2.5*
		Fuel cell	*1.5*
2025	**Long haul**	Diesel engine	*1.0*
		Hybrid diesel	*1.1*
		Battery electric	*2.0*
		Catenary electric	*2.3*
		Fuel cell	*1.4*
	Regional delivery	Diesel engine	*1.0*
		Hybrid diesel	*1.1*
		Battery electric	*2.2*
		Catenary electric	*2.5*
		Fuel cell	*1.5*

Source: JEC WTW v5

The efficiency advantage over combustion engines for electric drivetrain medium- and heavy-duty vehicles is not so great as for passenger vehicles, but still considerable. The most efficient configuration is catenary electric vehicles as they are not required to carry large batteries for power storage, but these are of course dependent on availability of catenary infrastructure. The results for 2025 electric drivetrain vehicles are better than or equal to the results for 2016, which reflects the relatively early stage of development of medium- and heavy-duty electric drivetrains.

2.2. California Air Resources Board

The California the Low Carbon Fuel Standard (LCFS) is a regulation requiring fuel suppliers in California to deliver GHG emissions intensity savings in the California fuel pool by generating or purchasing emissions reduction credits. The California Air Resources Board uses EERs to calculate the emissions avoidance credit to be given to electric drivetrain vehicles under the LCFS; these are listed in Table 3.

Table 3. EERs used for calculating credit generation under the California LCFS

Type	Powertrain	EER
Light duty	Battery electric car	3.4
	Fuel cell car	2.5
	Battery electric motorbike	4.4
Medium/heavy duty	Battery electric truck or bus	5.0
	Fuel cell truck or bus	1.9

Source: Cal. Code Regs. Tit. 17, § 95486.1 - Generating and Calculating Credits and Deficits Using Fuel Pathways (2021)

Under the LCFS, EERs are used in the calculation of the GHG emission avoidance credits that should be awarded based on the amount of energy supplied to a given vehicle type following this equation:

$$Credits = Energy \times \left(\left(CI_{target} - \frac{CI_{energy}}{EER} \right) \times EER \right)$$

The regulatory values in California for passenger vehicles are comparable to the estimated EERs for 2015 vehicles from the JEC WTW v5, but a little higher than the predicted 2025 values. The regulatory EER of 5 used for electric trucks and buses is high compared to the JEC WTW v5 values, the underlying analysis is described by CARB (2018).

3. Delivering electrical energy to transport

The efficiency of vehicles represents the "tank-to-wheel" part of the transportation system, but the overall energy efficiency of different energy/powertrain combinations is also affected by the efficiency with which primary energy is converted into a form that can be used by the vehicle, the "well-to-tank" part of the system. Renewable electricity can be used to provide energy for vehicles in three basic ways:

1. Electricity can be supplied directly to vehicles with electric drivetrains through battery charging or via a direct power connection such as a catenary wire.
2. The electricity can be converted to hydrogen through electrolysis, and the hydrogen can be supplied at hydrogen fuelling stations to vehicles with hydrogen tanks and fuel cells.
3. The electricity can be converted to hydrogen through electrolysis, the hydrogen can be used as a platform to synthesise liquid hydrocarbon fuels, and the liquid hydrocarbons can be supplied to vehicles with internal combustion engines (often referred to as 'electrofuels' or as RFONBOs[6]).

From the point of view of vehicle manufacturers, supplying electricity as electrofuels may seem the most convenient way to use renewable electricity to power transport, because if electricity can be used to produce liquid petrol or diesel then there is no need to change existing engines or fuelling infrastructure. Unfortunately, there are also downsides to this approach. Energy is lost through the chemical conversion processes to go from electricity to hydrocarbons, and sticking with internal combustion engines means failing to take advantage of the high efficiency of the electric drivetrain. The cost of electrofuel production may also be a barrier to deployment of the technology (Malins, 2017).

The JEC WTW v5 also includes a characterisation in the WTT section of the report of the potential energy efficiency of systems to supply hydrogen or electrofuels. Combining this information with the EERs from the TTW section of the report allows us to compare the overall efficiency of systems to deliver renewable electricity to transportation. Table 4 provides a characterisation of the expected efficiency of electricity supply to transport for the three energy supply systems. The efficiency values reported for hydrogen and electrofuel systems include consideration of electricity required for electrolysis, carbon capture and fuel synthesis, but do not include any additional heat required for the associated processes[7]. It is assumed that 15% of electricity supplied to battery vehicles is lost during the battery charge and discharge cycle (this is the JEC WTW v5 assumption for charging in 2025. The table shows two electrolysis options. Low temperature electrolysis is a more mature technology but is less efficient. High temperature electrolysis is a less mature technology. It has potential to be significantly more efficient in terms of conversion of electrical energy to chemical energy but requires additional heat inputs (this heat energy input is not considered in Table 4).

6 Renewable fuels of non-biological origin.

7 The Fischer-Tropsch fuel synthesis reaction is exothermic and would supply much but not necessarily all of the heat energy required for carbon capture

Table 4. Energy supply efficiency from electricity

Fuel	Supply efficiency	
	Low temperature electrolysis	High temperature electrolysis
Electricity via battery charging	0.85	0.85
Hydrogen for fuel cells	0.65	0.80
Electrofuels (with direct air capture of CO_2)	0.40	0.50

Source: JEC WTW v5

4. Comparing transport systems

Combining the WTT and TTW elements of the analysis enables us to compare the efficiency with which electricity could be used to displace liquid hydrocarbons in transport. Table 5 is based on 2025 vehicle characterisations from JEC WTW v5. In order to simplify the presentation, simple arithmetic averages have been taken across vehicle ranges for passenger BEVs and across medium and heavy duty for goods BEVs and FCVs. Results are presented for both the less efficient low temperature electrolysis process (top of the table) and the more efficient high temperature electrolysis (bottom of the table).

Table 5. Fuel displacement from the use of electricity in transport

Type	Powertrain	Electricity supply efficiency	EER	Relative efficiency (MJ fuel displaced per MJ of electricity)
Low temperature electrolysis				
Passenger	Petrol engine with electrofuel	0.4	1.0	0.4
	Battery electric	0.9	3.2	3.0
	Fuel cell	0.6	2.0	1.3
Goods	Diesel engine with electrofuel	0.4	1.0	0.4
	Battery electric	0.9	2.1	2.0
	Fuel cell	0.6	1.5	0.9
High temperature electrolysis				
Passenger	Petrol engine with electrofuel	0.5	1.0	0.5
	Battery electric	0.9	3.2	3.0
	Fuel cell	0.8	2.0	1.6
Goods	Diesel engine with electrofuel	0.5	1.0	0.5
	Battery electric	0.9	2.1	2.0
	Fuel cell	0.8	1.5	1.1

The results detailed in Table 5 show the much greater fuel displacement efficiency that can be achieved by using electricity directly in battery electric vehicles than by the production of electrofuels. Even with a high temperature electrolysis process, six times more fuel use can be displaced by the same amount of electricity with a battery electric passenger vehicle than by using electrofuels. For goods vehicles there is a factor four difference. Fuel displacement from converting electricity to hydrogen for use in fuel cell vehicles falls in the middle.

4.1. Biomass energy

The analysis can be taken one stage further by considering the potential fuel displacement efficiency from the use of biomass for energy. It is generally acknowledged that electrofuels and electric vehicle charging should ideally be supported by 'zero emissions' renewables such as wind and solar power, but the EU expects to continue using biomass for both electricity generation and liquid biofuel production for the foreseeable future, and therefore it is of interest to compare the efficiency with which hydrocarbon fuels could be displaced per unit of primary biomass energy. Table 6 shows the fuel displacement per unit of chemical energy ion biomass feedstock when the biomass is used either for electricity generation[8] or is converted to liquid fuel through a process of gasification and Fischer-Tropsch fuel synthesis. The efficiencies for both are taken from JEC WTW v5, and results are presented for the high temperature electrolysis case only. We also include a pathway for supply of hydrogen from biomass gasification directly to fuel cells, assuming a hydrogen production efficiency of 60% based on Binder et al. (2018)[9].

Table 6. Fuel displacement from the use of biomass in transport

Type	Powertrain	Biomass conversion efficiency	Electricity supply efficiency	EER	Relative efficiency (MJ fuel displaced per MJ biomass)
Passenger	Petrol engine with BtL biofuel	0.5	-	1.0	0.5
	Petrol engine with electrofuel	0.4	0.5	1.0	0.2
	Battery electric	0.4	0.9	3.2	1.1
	Fuel cell (hydrogen from biomass gasification)	0.6	-	2.0	1.2
	Fuel cell (hydrogen from electrolysis)	0.4	0.8	2.0	0.6
Goods	Diesel engine with BtL biofuel	0.5	-	1.0	0.5
	Diesel engine with electrofuel	0.4	0.5	1.0	0.2
	Battery electric	0.4	0.9	2.1	0.7
	Fuel cell (hydrogen from biomass gasification)	0.6	-	1.5	0.9
	Fuel cell (hydrogen from electrolysis)	0.4	0.8	1.5	0.4

8 Here we have used the thermal efficiency given by JEC WTW v5 for a dedicated 10 MW Integrated Gasification Combined Cycle biomass power plant.

9 Binder et al. (2018) present hydrogen production pathways with theoretical biomass to hydrogen efficiencies of 69% and 33% respectively.

Table 6 shows that the most efficient ways to power transport with biomass would be through electricity generation and supply of that electricity to electric vehicles or through hydrogen production via biomass gasification and supply of that hydrogen to fuel cell vehicles. It is significantly less efficient to produce electrofuels from biomass-based electricity than to produce biofuel from that biomass directly.

5. Supporting GHG avoidance

The large differences in energy use efficiency between fuels and powertrains have implications for the GHG emissions benefits that can be delivered, and this should inform the way that renewable energy use in different vehicles is credited under any revision to the RED.

Table 7 provides equivalence factors comparing the benefit from supplying energy to vehicles as electricity, as hydrogen or as electrofuels, compared to the use of ethanol in a combustion engine as a baseline. The first row shows the equivalence in terms of the transport work that can be done by a vehicle with one unit of delivered energy. The second row shows equivalence in terms of the GHG benefit that could be achieved (compared to the use of fossil fuels in an internal combustion engine) per unit of energy delivered when consuming electricity at the expected GHG intensity of the 2030 EU grid mix (48.8 gCO_2e/MJ, European Commission, 2021a). The third row shows equivalence in terms of the GHG benefit that could be achieved per unit of energy delivered when consuming zero carbon electricity. A megajoule of zero carbon electricity supplied to a battery electric vehicle allows the avoidance of 5.4 times more GHG emissions from fossil fuel use than is achieved by supplying a megajoule of ethanol with a 60% GHG saving to a conventional vehicle.

Table 7. Equivalence values

	BEVs*	FCEVs**	E-fuels in ICE	Ethanol in spark ICE (60% GHG reduction)
Equivalence by distance travelled per unit of energy delivered to vehicle	3.2	1.5	1	1
Equivalence by GHG saving delivered per unit of energy delivered to vehicle (electricity at 48.8 gCO_2e/MJ)	4.5	1.4	-0.01	1
Equivalence by GHG saving delivered per unit of energy delivered to vehicle (electricity at 0 gCO_2e/MJ)	5.4	2.4	1.7	1

**The BEV values use an EER averaged across the 2025 values from JEC for passenger cars, as passenger vehicles are likely to dominate electric vehicle markets in the near term.*

***The fuel cell values use an EER averaged across the 2025 values from JEC for goods vehicles, as fuel cells may play a larger role in heavy duty transport. For example European Commission (2018) states that, "Hydrogen and fuel cells can play an important role in the achievement of a low-carbon road transport system, in particular in long-distance transport, e.g. for long-haul heavy goods vehicles and coaches."*

6. Discussion

If the proposed transition of the Renewable Energy Directive from an energy-based target for the use of renewable energy in transport to a GHG saving based target for the use of renewable energy in transport goes ahead, it is important that GHG savings delivered by the use of electricity in battery or catenary electric vehicles and the use of hydrogen in fuel cell vehicles are fairly credited. This requires recognising that a unit of energy supplied to an electric drive vehicle allows more transport work to be done than delivering a unit of energy to an internal combustion engine vehicle. Delivering a megajoule of zero carbon renewable electricity to a battery electric vehicle delivers can be expected to do 3.2 times more transport work and deliver 5.4 times more GHG reductions than delivering a megajoule of RED II compliant ethanol to a combustion engine vehicle.

The proposed changes to the RED as part of the Fit for 55 package would not credit this greater energy efficiency directly by including an EER for electric vehicles. Instead, the proposal would have suppliers use a higher fossil fuel comparator value when assessing the GHG saving from renewable energy supplied for electric vehicles than when assessing the GHG saving from renewable liquid fuels (183 gCOe2/MJ when assessing the GHG benefits of electricity use instead of 94 gCO_2e/MJ). This use of a high emissions comparator allows the greater efficiency of battery electric vehicles to be partly recognised. Under this system, a megajoule of zero carbon renewable electricity supplied to an electric vehicle would receive 3.2 times as much credit as a megajoule of ethanol supplied to a combustion engine vehicle with a 60% reportable carbon saving. This is still significantly less than the 5.4 times difference in GHG emissions reductions delivered, but would be enough to provide a clear signal that the supply of renewable electricity to battery electric vehicles should be an important part of meeting the revised RED targets.

In conclusion, the most transparent way to recognise the greater efficiency of electric drive vehicles when the RED is revised would be through a multiplier. The JEC Well-to-Wheels study shows that a multiplier of 3.2 would be appropriate. The proposed approach of adopting a different fossil fuel comparator is less transparent but can fulfil a somewhat similar function in the legislation. If the differentiation of fossil fuel comparators was removed without reinstating a multiplier it would result in a serious under-crediting of renewable electricity supplied to electric vehicles and create an unlevel playing field.

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