applied sciences

Supporting information for Electricity generation in LCA of electric vehicles: a review

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List of Acronyms

ALCA: Attributional Life Cycle Assessment
ANL: Argonne National Laboratory
BEV: Battery Electric Vehicle
BG: BioGas
CEMS: Continuous Emission Monitoring System
CHP: Combined Heat and Power
CLCA: Consequential Life Cycle Assessment
CNG: Compressed Natural Gas
DSM: Demand Side Management
DSO: Distribution System Operator
EEA: European Environment Agency
eGRID: Emissions & Generation Resource Integrated Database
EIA: Energy Information Administration
ENTSO-E: European Network of Transmission System Operators for Electricity
EPA: Environmental Protection Agency
EREV: Extended Range Electric Vehicle
ESA: Energy System Analysis
EV: Electric Vehicle
FCEV: Fuel Cell Electric Vehicle
GHG: GreenHouse Gas
GREET: Greenhouse gases, Regulated Emissions and Energy use in Transportation
HEV: Hybrid Electric Vehicle
ICEV: Internal Combustion Engine Vehicle
IEA: International Energy Agency
IGCC: Integrated Gasification Combined Cycle
IPCC: Intergovernmental Panel on Climate Change
LCA: Life Cycle Assessment
LCI: Life Cycle Inventory
LCOE: Levelised Cost Of Energy
LPG: Liquid Petrol Gas
MEF: Marginal Emission Factor
NEEDS: New Energy Externalities Development for Sustainability
NERC: North American Electric Reliability Corporation
NGCC: Natural Gas Combined Cycle
NGCT: Natural Gas Combustion Turbine

NORDEL: Nordic electric system operators
PEM: Partial Equilibrium Model
PEV: Plug-in Electric Vehicle
PHEV: Plug-in Hybrid Electric Vehicle
PHFCV: Plug-in Hybrid Fuel Cell-Battery Vehicle
PV: PhotoVoltaics
REN: Redes Energéticas Nacionais (Portuguese TSO)
RES: Renewable Energy Sources
TSO: Transmission System Operator
VMT: Vehicle Miles Travelled
WtW: Well-to-Wheel

In Figure S1 are listed the Greenhouse gas emissions of electric vehicles found in the literature. Since results in the literature are expressed according to different functional units, they have been transformed in the most common functional unit (g CO_2-eq/kWh) in this review, when enough information allows for the conversion. If more than a single value is provided, bars represent the average value, while the error bars delimit the upper and lower value. Red dots indicate the GHG intensity of the selected electricity mix, where it is made explicit or it has been possible to obtain it a posteriori. For the numeric values, see Table 1.

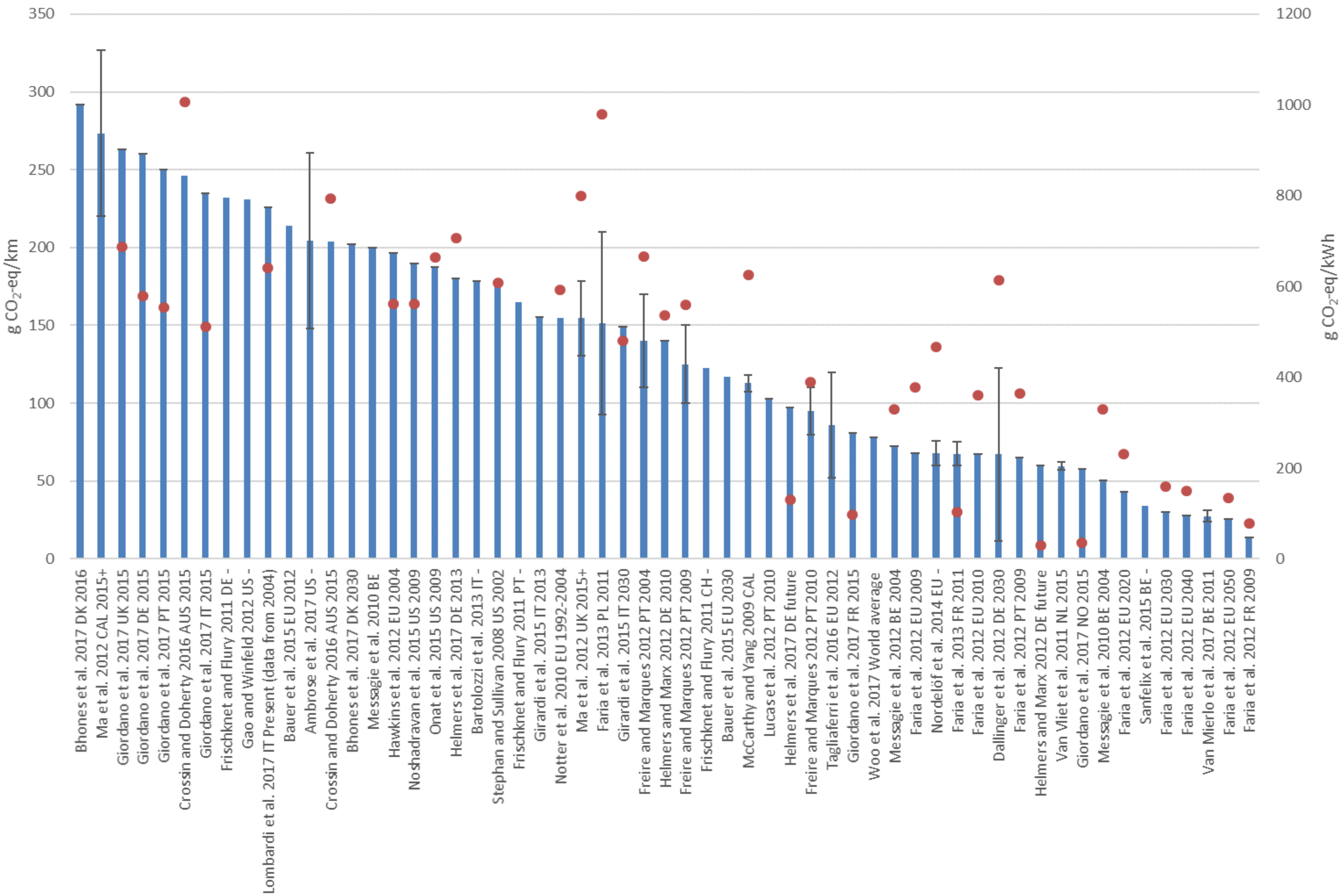

Figure S1. The literature results normalised at the most common indicator "g CO_2-eq/km" (blue bars, left axis). If a study presents more than one value, the average value has been reported with the associated range. For studies that explicit electricity mix intensity, they are represented with a red dot (right axis).

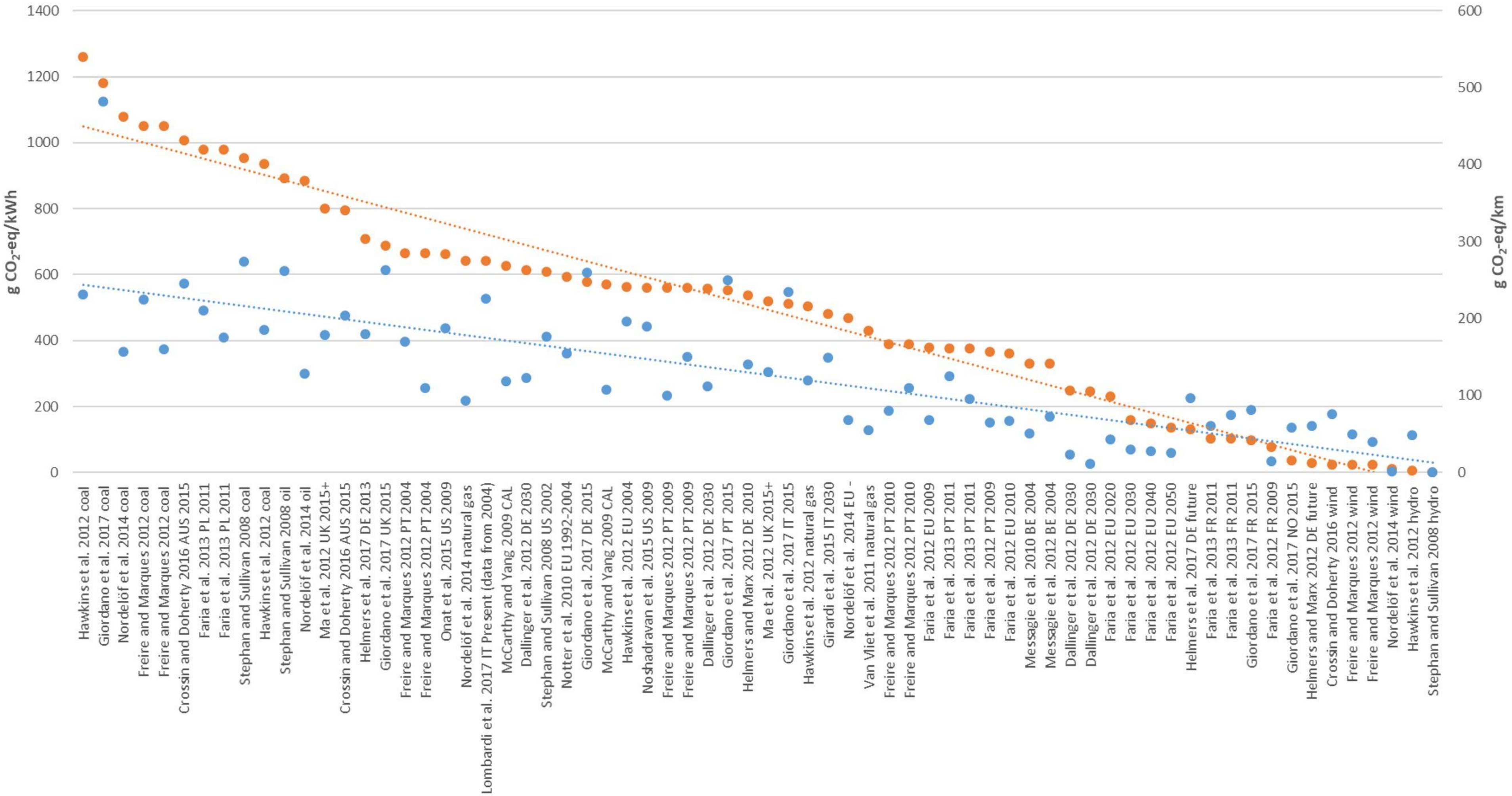

Figure S2. Studies reporting g CO_2-eq/km and g CO_2-eq/kWh in descending order of electricity carbon intensity

Table *S1*. Literature results and recommendations for practitioners and policy makers

	Literature Review	Recommendation for LCA Practitioners	Recommendation for Policy Makers
Goal	Often missing or incomplete. Only four articles out of 44 abided by all the requirements from ISO 14040. Most of the studies omits application and intended audience.	Every requirement of a clear goal (see ISO 14044) needs to be clearly specified before carrying out the analysis	Consider neglecting studies with unclear goal. Carefully see if the goal matches with the decision to be taken.
Scope	Not always in line with the goal, also because of the lack of clear goal definition. Wide range of scopes have been found in the literature (WtW or complete LCA, fleet based or single vehicle based, at local scale or nation-wide) but all aimed at generically inform the policy makers on the environmental performance of electric vehicles (EVs)	Scope must put into practice the definition of the goal	See if the scope (especially time horizon and the scale of the study) suits the scope of the political decision to be evaluated
Modelling Choice	Selection of Attributional or Consequential modelling choice are rarely justified	Modelling choice has to be a direct consequence of the goal and scope definition. Needs for a shared framework on how to implement different modelling choices	-
Time Horizon	Time dimension is generally neglected (see Figure 5). Many studies refer to a not better specified "present". When time horizon is specified, there are inconsistency between time-related aspects (e.g. EV penetration rate, electricity mix, vehicle technology)	Time horizon and the scale of the analysis have to be in line with the goal. All the other variables have to be consistent with each other and time related parameters need to cohere with the time horizon (e.g. performance of the vehicles and components, penetration rate, etc.)	
Scale Of The Analysis	Vehicle based LCAs are the majority compared to fleet based LCAs. Penetration rate of EVs are often neglected or not consistent with the declared time horizon		Results from single technology comparison (e.g. EVs performance versus ICEVs) cannot be applied to nation-wide scale
LCI – Electricity mix selection	Selection of average or marginal electricity mix is rarely justified or explained in the bigger context of Attributional verses Consequential modelling choice. In some articles, in a paradoxical inversion is the selection of the electricity mix that determines the type of analysis (ALCA or CLCA) Many ALCA rely on old datasets for electricity mixes. Historical data are used also for marginal mix and its results are applied to future situations	Selection of the electricity mix has to be in line with the modelling choice; it is not the selection of the electricity mix that determines the type of study (ALCA versus CLCA). Especially when relying on a database (e.g. EcoInvent, GREET, Gabi Database) practitioners need to be aware of the quality of the dataset they are using. Definition of marginal mix has to be consistent with time horizon and scale	
Results	Results are diverging but could be not necessarily conflicting (if equipped with clear goal and scope definition). The GHG intensity of the electricity mixes selected in the studies explains 70% of the variability found in the literature results		

A tentative modelling framework, derived from the gaps found out in the literature, is presented in Table S2. In the table the most recurring applications (explicit or inferred) are put into a scheme, where their time horizon and scale are defined, along with the suggested method to select (or calculate) the electricity mix.

The most relevant one, the transition to electric mobility, implies a long term scenario and nation-wide scale. The mutual effect of transport and energy sector has to be investigated through ESA.

According to the ILCD handbook this situation is part of the "meso/macro-level decision support" (situation B in Table 2) and thus require consequential modelling.

The use of short term marginal mixes comes into practice when the focus of introducing electric vehicles in the grid is to help balancing loads, due to the flexible nature of EVs charging. In this sense the political decision matching with this goal is the incentives to specific charging strategies (smart charging, V2G development etc...). The dimension of the changing and the time horizon has once again to be taken into consideration when selecting the calculation method to define the marginal mix: regression models based on historical data apply only for small load changes and near future (see paragraph 3.2). If bigger load and a change in generation capacity are expected, optimisation models are more suitable.

Table *S2*. Framework for the main applications found in the literature

Policy Level	Goal	Time Horizon	Scale and Potential Effect from The Grid	Electricity Mix Calculation Method	Electricity Mix
Transitioning to Electric Mobility	Effects of adding significant number of EVs/displacing ICEVs with EVs	Future	Nation-wide Fleet based LCA Mutual effects between transport and energy sector to be investigated	Simple long term marginal Energy system analysis	Long term marginal
Charging Strategies development	Effects of load balance from EVs (considering smart charging, V2G, etc.)	Both present and future	local (handling bottleneck) and nationwide. Potential grid optimisation due to flexible load	both bottom up approach (only for near present and small changes on the grid) and top down approach	Short term marginal
Incentives for Household Purchasing of Electric Vehicles	Effects of introducing a small amount of electric vehicle in the present market	Present (EVs expected to self-sustain in the future)	small changes on the grid	$= \frac{\text{total load}}{\text{total electricity production}}$	Average