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Modelling electro-mobility: an integrated modelling platform for assessing European policies

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Abstract

Recently, the European Union (EU) adopted the Directive on the deployment of alternative fuels infrastructure, which defines minimum requirements on alternative fuels infrastructure build up, including recharging points for electric vehicles. Moreover, the European Commission is currently working towards a Communication on decarbonising the transport sector, including an action plan on second and third generation biofuels and other alternative, sustainable fuels. Various Member States have set up incentives to foster electrified or low-emission vehicle purchases. The Joint Research Centre, as the European Commission's in-house science service, has created a suite of models on electro-mobility, which serves to assess policies towards electrification of road transport and their effects on energy demand, emission reduction and costs. The models are soft-linked and the structure is flexible enough to make sure that the appropriate tools can be used for various studies. The models within this suite include:

- A Market Agent model that captures the dynamics between automobile manufacturers, infrastructure providers, authorities and users in order to model competition between and transition of current and future powertrain technologies;
- A Fleet Impact tool, containing up-to-date vehicle stock data and energy and emission factors of all vehicle types in the EU, as well as fuel consumption and (real world & type approval) emission calculation, both for Tank-to-Wheel and Well-to-Wheel
- An EV-Charging model that estimates the energy-consumption of electric vehicles and calculates their power demand (load) on the basis of usage statistics (e.g., daily distance travelled, parking duration, number of daily trips)

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- An Energy System Model (JRC-EU-TIMES) that models energy technologies' uptake and deployment and their interaction with the energy infrastructure from an energy systems perspective
- Various others depending on the needs of the assessment to be made.

This paper shows key results of studies that were performed with the JRC integrated electro-mobility modelling platform.

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Keywords: Electro-mobility; transport decarbonisation; alternative fuels infrastructure; transport modelling

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1. Introduction

In Europe and globally several policies and incentives are being designed and implemented to promote electro-mobility, as part of aspirations to decarbonise the road transport sector. In particular, the White Paper on Transport has set the targets of a 60% reduction of transport carbon emissions by 2050 versus 1990 levels and the phase-out of conventionally fuelled vehicles in cities by 2050 (European Commission, 2011).

Still, electric vehicles (EV) have a limited presence in the lives of the average European citizen. It is unclear if the ambitious goals of vehicle deployment that were envisaged by several member states can be achieved. Nevertheless, the EU EV market has seen a lot of momentum during the past five years (Thiel et al., 2015). In European countries with the strongest incentives for the purchase and use of EVs, like Norway and the Netherlands, sales of EVs rose to up to 5% of the new vehicle market.

2. Methods

In this chapter we briefly describe the main features of the models that are currently used at the JRC to assess the role, potentials, and challenges for electro-mobility in support to the: (i) implementation of the EU directive on the deployment of alternative fuels infrastructure (EU, 2014a); (ii) achievement of the long-term Transport Whitepaper Goal of cities free of conventionally fuelled cars (European Commission, 2011); (iii) decarbonisation and electrification of the transport sector and integration of the energy and transport systems as described in the Energy Union package (European Commission, 2015). Table 1 provides a first overview on the models and their use within the JRC electro-mobility modelling platform.

Table 1. The JRC Electro-mobility models.

	PTT-MAM	Dione	EV-charge	GIS EV Infra	JRC-EU-TIMES
Full model name	Powertrain Technology Transition Market Agent Model	Fleet impact model	Electric vehicle charging scenario model	GIS based Charging Infrastructure allocation tool	JRC-EU-TIMES energy system optimisation model
Scope and use within Electro-mobility modelling platform	Scenario building for future car and LCV powertrain market deployment in EU	Road transport emissions and energy demand (WtW) in EU	Time patterns of EV induced electrical loads and load shift scenarios in EU	Optimal geospatial allocation of EV charging infrastructure on city/ region level	Role and impact of electro-mobility within energy system (decarbonisation) scenarios in EU

2.1. Powertrain Technology Transition Market Agent Model (PTT-MAM)

The PTT-MAM model is a comprehensive System Dynamics simulation model, running up to 2050, employing a representative market-agent approach and incorporating major factors that influence the technology transition of light-duty vehicles in the EU road transport sector (Harrison et al., 2014). Included within the model are all 28 EU member states, 16 powertrain options (including alternative fuel ICEV, full and plug-in hybrid (PHEV), BEV and FCV) and 3 user categories (private, public and fleet). The extensive model, which comprises of over 700,000 elements, was built around the concept of four interacting agents representing the roles of the automobile manufacturer, infrastructure (and maintenance) provider, users and authorities, as illustrated in figure 1. The model has a high degree of flexibility, despite its complexity, allowing the user to create many possible scenarios, based on assumptions regarding exogenous variables affecting market conditions (e.g. GDP growth, oil price, learning rates) and policy implementation (e.g. vehicle purchase subsidies, fleet emission targets). User purchase decisions are made using a simple choice model based on key attributes of each vehicle type, which evolve endogenously over time as the manufacturer invests in R&D in response to emission regulations. The main output from the model is the annual powertrain market shares. Many other relevant factors (such as infrastructure availability) are also captured, allowing a more detailed investigation and understanding of the evolution of the e-mobility market. The model seeks to integrate a wider range of market, industry and technology dynamics compared to other known models to date.

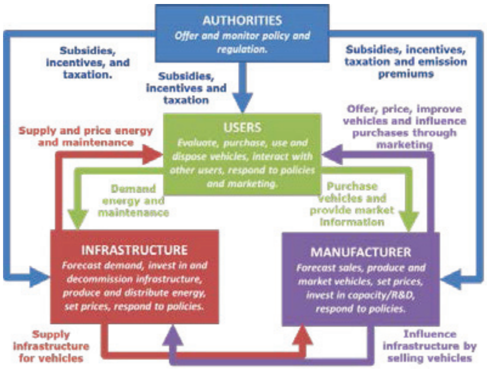

Fig. 1. Relationships in PTT-MAM.

2.2. Fleet impact model Dione

DIONE is a Fleet Impact Model able to assess the impacts of changes in the European and MS road transport fleet characteristics up to the year 2050. It is a flexible tool which can be used to assess the impact of new emission limits in road transport, the effect of new and advanced technologies and other policy measures like scrappage schemes. Main variables can be defined by the user, including vehicle stock, new registrations, survival rates, activity, efficiency, fuel mix shares used by flex-fuel vehicles (FFV) including PHEV, fuel pathways for Well-to-Wheel energy consumption and emissions, biofuel admixture shares for conventional fuels, and driving patterns. For both energy consumption and greenhouse gas (GHG) emissions, DIONE can provide current and future real world Tank-to-Wheel (TtW) as well as Well-to-Wheel (WtW) results. For CO_2 emissions, the model can calculate with type approval or real world values. DIONE includes a cost module which determines additional costs for achieving given efficiency targets for conventional passenger cars.

DIONE contains a calibrated baseline which is consistent with the country-specific stock and activity data collected in the project TRACCS, and is taken forward following the trends of PRIMES 2012 baseline scenario with adopted measures. Fuel consumption and emission calculation for combustion engine vehicles is based on COPERT 4 v.11 road transport emission inventory software. For alternative fuel vehicles, an energy and emission calculation methodology has been developed which takes account of vehicle characteristics, trip lengths and speed distributions. More information on the model can be found in Krause et al. (2015).

2.3. Electric vehicle charging scenario model (EV-charge)

The model derives representative charging profiles based on the driving profiles of car drivers, currently driving conventional vehicles. It is based on the travel diaries that were collected from 3726 car drivers (Pasaoglu et al., 2012). Current model coverage is: DE, ES, IT, FR, PL, UK. Representative charging profiles are derived from the driving and parking patterns with the help of battery storage estimates and re-charge characteristics. The tool provides the basis for EV induced electricity load curve scenarios in Member States or regions. The model creates input to the downstream models analysing electricity grid and market aspects. More information on the EV-charge model can be found in Pasaoglu et al. (2013).

Version 2 of the model, currently under development, is based on a more extensive analysis of individual mobility behaviour. Driving profiles were obtained from three datasets: the mobility data used in version 1, floating-car data (de Gennaro et al., 2014, Donati et al., 2015), and data collected during the EU-funded Green eMotion project (Cochero et al., 2015, Donati et al., 2015). The Floating-car data were collected via on-board data loggers on conventional vehicles that were driven in two medium-sized Italian cities (Modena and Florence), during May 2011. A total of approximately three million trips were analyzed. The Green eMotion database contains data for electric vehicles, primarily Mitsubishi i-MiEV and its European cousins Peugeot iOn and Citroen C-zero. The vehicles were driven in 11 regions in six European countries (DK, FR, DE, IE, IT, SE). In addition to data collected for conventional vehicles (e.g., trip distance and duration, parking duration) the Green eMotion (GeM) database contains information specific to electric vehicles: for example, electric energy consumed per trip, battery State-of-Charge (SoC), power flows from the electricity grid. For all the mobility variables extensive descriptive statistics were drawn up.

2.4. GIS-based Charging Infrastructure allocation tool (GIS EV Infra)

The model is based on the use of an open source Geographic Information System application (QGIS) and has two different approaches depending on the area of study. The first approach is for a city level where a set of geospatial data is being collected and edited in order to be transformed into raster layers. Based on different weighting factors a map is created with cells of 100x100m. This map indicates the optimal areas of a city where EV charging infrastructure should be placed according to specific scoring levels.

The second approach is for a regional/national level and has as a target the allocation of infrastructure every x km, where x is calculated based on the Donati et al. (2015). First, the highways are being studied based on the relevant geospatial polyline shapefile with the set of the available gas stations and rest areas (as a geospatial point shapefile) along the highway. The suitable and optimal stations/rest areas are selected based on an algorithm that compares all the distances between them. For the rest of the regional network, the geospatial shapefile of the main rural roads is used and split in a way that there is adequate infrastructure every x km that would facilitate an EV to cross the whole region. More information on the model can be found in Gkatzoflias et al. (2016).

2.5. JRC-EU-TIMES energy system optimisation model

The JRC EU TIMES model, developed by the JRC and based on the TIMES[1] model generator, represents the EU 28 energy system from 2005 to 2050, where each member state is one region. It also includes Switzerland, Iceland and Norway as well as the Western Balkan countries. JRC-EU-TIMES explicitly considers two energy supply sectors – primary energy supply and electricity generation – and five energy demand sectors – industry; residential; commercial; agriculture; and transport. The energy system technology mix that satisfies the demand for useful energy services at the least cost is then derived under the paradigm of a central planner perspective with perfect foresight, subject to several constraints, such as the maximum technical potential for renewable energy sources, primary supply constraints, technological development constraints, and greenhouse gas emission constraints.

The most relevant outputs are the annual stock and activity of energy supply and demand technologies for each region and period. This is accompanied by associated energy and material flows including emissions to air and fuel consumption, detailed for each energy carrier. Besides technical outputs, for every year is obtained the associated operation and maintenance costs, the investment costs for new technologies, all energy and materials commodities prices (including for emissions if an emission cap is considered). As such the JRC-EU-TIMES model is useful to

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[1] TIMES: The Integrated MARKAL-EFOM System; MARKAL: Market Allocation; EFOM: Energy Flow Optimisation Model

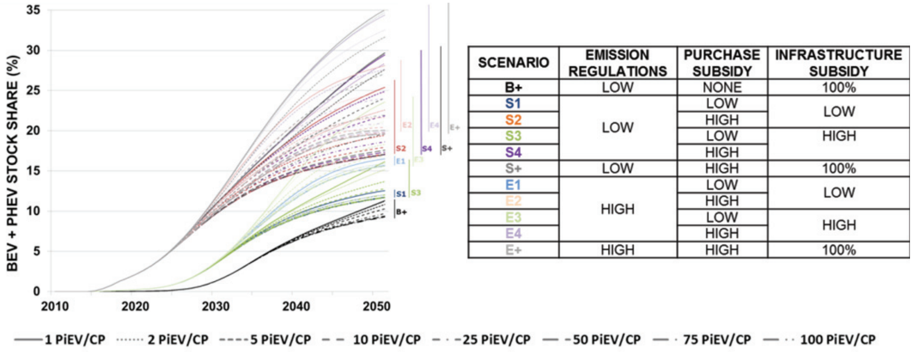
analyse the interaction between the deployment of electro-mobility and the wider energy system, and there specifically the power sector. More information on the JRC-EU-TIMES model can be found in Simoes et al. (2013).

3. Model results

With the models described above we have analysed various aspects related to electro-mobility scenarios and impact studies. In this chapter we show some exemplary results of those studies.

3.1. PTT-MAM studies on the interaction between charging point infrastructure provision and electric vehicle uptake

The PTT-MAM has been employed to investigate the relationship between EV uptake and the provision of charging infrastructure (Harrison et al., 2014), which is often thought to be a "chicken-and-egg" type problem. Using the Alternative Fuel Infrastructure Directive (EU, 2014a) as a starting point, and set within the context of the EU new fleet emission regulations (EU, 2014b) and possible subsidy regimes, the results from numerous scenarios on resultant stock share of plug-in Electric Vehicles (PiEV) is presented in figure 2. We identified important interactions between alternative powertrain technologies and that the fleet emission regulations aimed at manufacturers have a greater long term impact on sales than subsidies aimed at users. However, subsidies for infrastructure, based on a desired ratio of Plug-in Electric Vehicle to Charging Point (PiEV/CP), would seem to only begin to make an impact on EV sales when the stock share is over 5%. Moreover, this ratio seems to be optimal at around 10 PiEV/CP, as reducing this rapidly increases charge point installation and associated costs with little additional EV market share. As such, efforts to increase the provision of charging infrastructure should take a long term view.



SCENARIO	EMISSION REGULATIONS	PURCHASE SUBSIDY	INFRASTRUCTURE SUBSIDY
B+	LOW	NONE	100%
S1	LOW	LOW	LOW
S2		HIGH	
S3		LOW	HIGH
S4		HIGH	
S+	LOW	HIGH	100%
E1	HIGH	LOW	LOW
E2		HIGH	
E3		LOW	HIGH
E4		HIGH	
E+	HIGH	HIGH	100%

Fig. 2. PiEV Stock Shares from PTT-MAM Scenarios.

3.2. Dione study on passenger car CO_2 targets

The DIONE model is employed to provide scenario analysis for road decarbonisation policy options, especially road vehicle CO_2 targets. As a first step, two different approaches have been analysed for reaching an EU new passenger car (PC) type-approval (NEDC-based) target of 70g CO_2/km in 2025, namely a) by increasing internal combustion engine vehicle (ICE) efficiency and b) by market introduction of battery electric vehicles (BEV). While it is unlikely that a single vehicle technology will be employed to reach a given passenger car emission reduction target, it was warranted to analyse clear-cut scenarios in a first step in order to better differentiate their effects, while mixtures of measures will be examined at a later point.

The inbuilt DIONE baseline includes ICE vehicle fuel efficiency improvement by roughly 33% from 2010 throughout 2020, thereby reaching the present targets for new passenger car fleet emissions of 130g CO_2/km in 2015 and 95g in 2020. In order to reach a 2025 target of 70 g CO_2/km, in the ICE efficiency scenario (ICEeff), a corresponding further improvement from 2020 to 2025 is assumed.

To reach the 2025 target through BEV market introduction in the EU28, in the Electric Vehicle scenario (EVscen), an increasing number of new BEV registrations are introduced instead of ICE car registrations. BEV annual market shares increase from 0.5% of new PC registrations in 2015 to 26% in 2025 (DIONE baseline: 3% in 2025), building up a BEV share of 5% of PC stock by 2025 (compared to less than 1% in the DIONE baseline). For both scenarios, electricity carbon intensity was set to the EU Reference Scenario 2013 (European Commission, 2013).

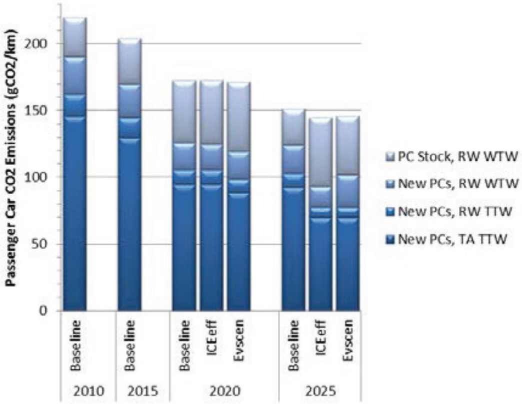


Fig. 3. EU28 passenger car CO2 emission (in g/km) development calculated for DIONE baseline (Base), efficient ICE (ICEeff) and BEV market introduction scenario (EVscen). The lowest segment of each column shows annual new passenger car registrations' average specific CO2 tank-to-wheel (TTW) emissions as measured by the type approval (TA) procedure. The segments placed above show additional emissions for going from type approval to real world (RW) emissions calculation, then for going from tank-to-wheel to whell-to-wheel (WTW) emissions, and finally for considering passenger car stock instead of just new registrations.

Figure 3 shows the development of CO_2 emissions from 2010 to 2025 for the DIONE baseline and the two other scenarios. Each bar as a whole represents average CO_2 emissions per kilometre for the EU passenger car stock calculated on a real-world, well-to-wheel basis, which is the most encompassing metric provided by DIONE. In the figure this metric is further broken down in (i) type approval TTW new car emissions, i.e., the emission metric currently used for EU PC CO_2 emission targets, (ii) real-world TTW new car emissions, and (iii) well-to-tank (WTT) (upstream) emissions. It can be seen that the target of average new passenger car emissions of 70 g CO_2/km by 2025 is met in both scenarios, but not under baseline conditions, where 2025 new PC emissions are 93 g CO_2/km. Highest WTT emissions of 24 g CO_2/km occur for the EV scenario, due to the higher upstream CO_2 intensity of electricity compared to fossil fuels WTT emissions according to the scenario settings. However, within a strong BEV market introduction scenario, it might be argued that this factor needs to be set to zero, as additional electricity for mobility will have to be carbon-free due to the emission cap in place for electricity production under the emissions trading scheme (ETS). For assessing the climate impact of passenger cars, not only the newly registered cars, but the whole stock needs to be taken into account. It can be seen that in 2025 passenger car fleet emissions are 145 g CO_2/km for the efficient ICE scenario and 146 g CO_2/km for the EV scenario, while the baseline stock emissions are at 152gCO_2/km. This sums up to more than twice the 70 g CO_2/km that are achieved by the new fleets in type approval TTW mode.

As preliminary conclusions the present analysis underlines that it is important not only to look at the regulated metric, but also to take into account real world effects and upstream emissions, and that it is crucial to put regulation into place in a timely manner, as it will take some time to bring home fleet emission effects. It is also shown that electric vehicles can make an important contribution to PC CO_2 emission reduction, especially for strict emission reduction targets, as the assumptions on ICE efficiency improvement made here may actually be at the upper limit of achievability. Road vehicle electrification can also bring home benefits for reduced oil dependence, local air quality and noise reduction, but its CO_2 emission reduction effect depends strongly on electricity decarbonisation. In the near future, follow-up work will focus on refining scenarios and extending the analysis beyond passenger cars to light commercial as well as heavy duty vehicles.

3.3. Electric vehicle charging scenario model (EV-charge)

In a study, in which we considered a scenario with 10% electric vehicles in the car fleet we found that unrestricted charging could lead to increase power peaks as likely charging events would coincide with other load peaks. Figure 4 shows on the left side the situation for Germany, UK, France, Spain, Italy, and Poland, when every electric vehicle would be recharged when parked for a longer duration. The figure reveals that the EV induced loads would create a peak in the late afternoon hours. This is the period in which load peaks typically occur in most member states already today, without significant EV on the road. The right side of figure 4 shows the situation when the time of EV charging is managed and where compliant with the driving needs loads can be shifted to the night, filling power "valleys".

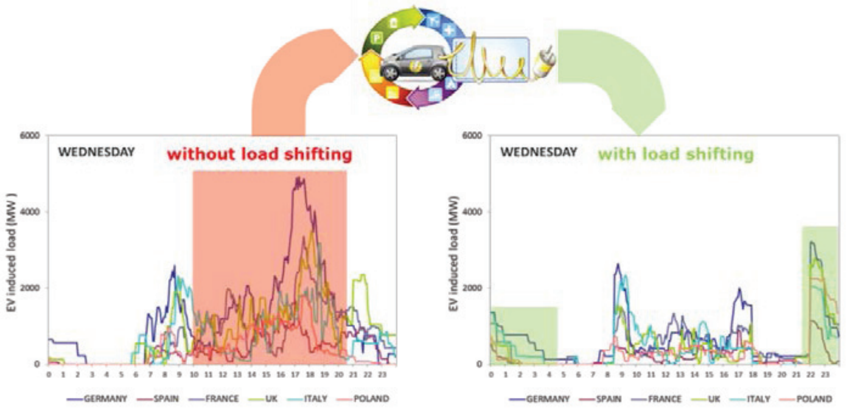


Fig. 4. Scenario of EV induced loads without and with load shifting in selected member states.

The analysis of driving behaviour incorporated into version 2 of the EV-charge model showed significant similarities between the three datasets (Survey, Floating-car, GeM), in particular in the general form of the distributions of the distance travelled per trip and duration of parking. Nevertheless, some differences between battery electric cars (GeM data) and conventional vehicles (Floating-car data) were noted. The average and median daily distances travelled by BEVs (cars) were approximately 20% less than the distances travelled by conventional vehicles (in Modena and Florence, the two cities studied via Floating-car data), whereas the mode was larger. The analysis of the electric cars showed that 80% of the trips covered a distance less than 10 km, 80% of the trips lasted less than 22 min, and 80% of the daily mobility length, the distance travelled per day, was less than 50 km. The daily mobility distance is, thus, well within the real range for most BEVs (cars) currently available on the EU market. The corresponding values for conventional mobility (floating-car data) are higher. The 80th percentile of single-trip distance is 15 km, and it is around 65 km for the daily mobility length.

We estimated the electric energy consumed per kilometre by the battery-electric cars that participated in the GeM project, mainly small, A-segment cars. We found that the median energy consumed was 186 Wh/km with a variation of 55 Wh/km. A linear regression model (applied only to trips that covered a maximum of 50 km) also predicted an electric energy consumption of 182 Wh/km. Note that a plain average of the distribution of the energy consumed per kilometre results in a consumption of 208 Wh/km, a manifestation that its distribution is non-Gaussian. We suggest that the median, being a robust estimator, is a preferable choice to estimate energy consumption. The energy consumption was determined to depend on the ambient temperature, the minimum consumption occurring when the external temperature was in the range approximately 12 °C to 20 °C. This dependence was attributed to the use of on-board heating/cooling systems. Figure 5 shows the average and median energy consumption for all GeM electric cars that provided consumption measurements as a function of period of the year (month).

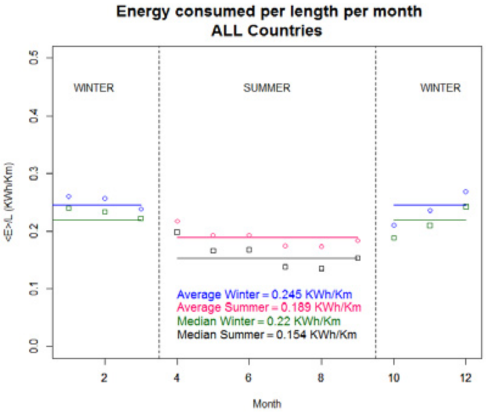


Fig. 5. Monthly energy consumption per kilometre of A-segment BEV, subdivided in winter and summer.

3.4. GIS EV Infra study for the city of Bolzano and the province of Alto-Adige (Italy)

A study was carried out with the collaboration of the European Academy of Bozen/Bolzano (EURAC) in order to define the optimal areas for allocation of EV charging infrastructure in the city of Bolzano and the province of Alto-Adige. The municipality and the electricity network company managed to gather and provide (through EURAC) all the required geospatial input data for the study on city level: (i) residential statistics (population density), (ii) parking places and lots, (iii) electrical power grid, (iv) public transport stations, (v) public access buildings (hospitals, museums, universities etc.), (vi) shopping/food areas (stores, malls, restaurants etc.). After editing the data and transforming them in raster layers of 100x100m cells, weighting factors were applied. With map algebra the resulted allocation map was created. Figure 6 shows the resulting allocation map. Areas in red indicate a high score for allocation of charging points whereas yellow represents a medium score and blue a low score. Normal chargers could be placed in the red and yellow areas whereas fast chargers could be placed at specific points in the red areas. These could be for example gas stations, transport stations and parking places with limited allowed parking time.

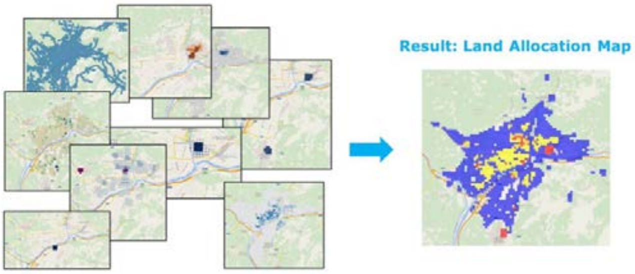


Fig. 6. Using map algebra and weighting factors on raster layers to create a land allocation map.

On a regional level, first the highways that cross the province of Alto-Adige and the set of the gas stations that are available along the road were studied. Based on the report Donati et al. (2015), a maximum range of 60 km (actual road distance and not Euclidean distance) had to be covered by each charging point. After calculating all the distances between all the stations and the beginning and end of the highway, a map was created with the optimal allocation of infrastructure on specific gas stations (figure 7). Then, the main rural road network was studied and it was split every 30 km to indicate the suggested areas for installing charging points that could facilitate an EV to go across the whole province (figure 7). The segments length is smaller than the distance of the 60 km maximum range, as a safety margin was applied in order to take account of the omission of smaller secondary roads (with lengths <20 km) from the initial file. Furthermore, on rural roads the access to the charging points is available from both directions giving the possibility to a driver reaching the border of the province and returning back to the last charger (even if the last one is placed 30km before the border). The total number of charging points suggested is 36. All the chargers included in the regional/national level analysis should be fast chargers since they are used mainly by drivers in order to complete journeys that go beyond the electric range of their cars. Changing appropriately the layers, buffer zones and weighting factors, the methodology could be used for solving any kind of optimal allocation problem as for example the optimal location of transit points for urban logistics.

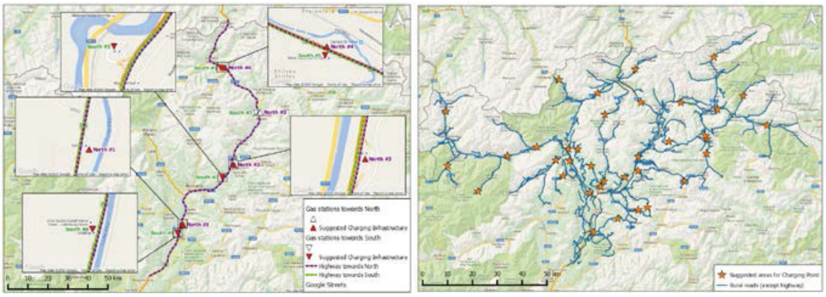


Fig. 7. Suggested gas stations for installing charging infrastructure on the highway (left) and on the main rural roads (right) at the province of Alto-Adige (Italy).

3.5. JRC-EU-TIMES study on role of electric vehicles to decarbonise EU road transport

In a study on the role of the EU car CO_2 regulation to achieve lower CO_2 emissions from transport by 2030 (Thiel et al., 2014) we found that electro-mobility can be a cost-effective way to meet the CO_2 targets and support the decarbonisation of road transport in the EU. Figure 8 shows the car technologies that the JRC-EU-TIMES model deploys in order to meet the decarbonisation target in a cost minimal way. The figure reveals how more and more efficient cars enter the market and from 2020 onwards a larger amount of electric vehicles are deployed. Electric cars are treated as zero emission vehicles in the current EU car CO_2 regulation. CO_2 emissions from electricity generation are capped through the ETS system. In our model runs the larger deployment of electric vehicles leads also to an accelerated decarbonisation of the power sector, as the higher electricity demand from electric vehicles needs to be met with low carbon electricity sources.

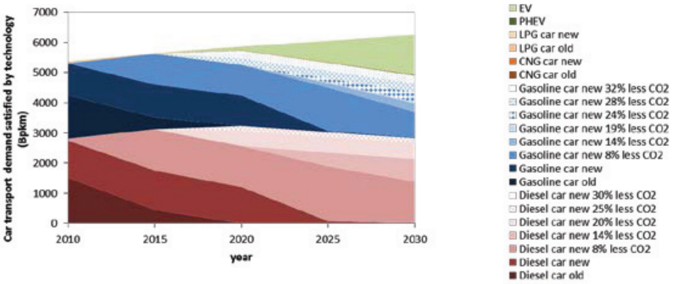


Fig. 8. Technology deployment in the JRC-EU-TIMES model under a transport decarbonisation scenario.

4. Conclusions

The JRC integrated electro-mobility modelling platform has been used to analyse various aspects of alternatively fuelled vehicles, especially electrified vehicles. The tools assess (i) interaction between infrastructure provision, user, vehicle manufacturer, and policy, (ii) policy options to ensure sufficient and synchronised infrastructure/vehicle deployment, (iii) road transport decarbonisation options and potential impacts on the fuel/energy supply.

Results from model based analyses that were performed with selected tools of the JRC integrated electro-mobility modelling platform allow the following conclusions. Electro-mobility is a promising option to decarbonise passenger car and light commercial vehicle (LCV) transport. Depending on the further evolution of battery costs electric vehicles can become a cost effective option to meet stricter CO_2 targets for cars and LCV. Electric vehicles can greatly contribute to reduce other regulated emissions and improve the air quality in urban areas. Furthermore, road transport electrification can reduce the oil dependence of transport. For an overall improvement of WTW GHG emissions it is important that the electricity used for transport is mainly generated from low carbon sources. Options for load shift for the electricity supply can support reducing the CO_2 footprint of the electricity mix. The influence of climatic conditions on the efficiency of cars is greater for electric vehicles than for ICE propelled cars. Our analyses also indicate that the discrepancy between type approval energy consumption values and field test measurements may be higher for electric than for ICE vehicles. A successful market penetration of alternative vehicles is the result of complex interactions between users, manufacturers, infrastructure provision, and policies. The deployment of alternative vehicles needs to be accompanied by the roll-out of an alternative fuels infrastructure. For electric vehicles we found that the ratio of one public charge point per ten electric vehicles seems to be optimal from a cost-benefit perspective. However, more detailed cost-benefit analyses may be required to substantiate this finding further and also to assess its validity across European regions.

The JRC integrated electro-mobility modelling platform has demonstrated its usefulness for policy support in the overall context of the energy, transport, and climate policy agenda of the European Union.

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