

Impacts of Low Carbon Fuel Standards in Transportation on the Electricity Market

Ahmad Karnama

Faculty of Engineering - University of Porto (FEUP)

Porto, Portugal

João Abel Peças Lopes

Faculty of Engineering - University of Porto (FEUP) & INESC TEC

Porto, Portugal

Mauro Augusto da Rosa

Federal University of Santa Catarina (UFSC),

Florianópolis, Santa Catarina, Brazil

Electric Vehicles (EVs) are increasing the interdependence of transportation policies and the electricity market. EMMEV (Electricity Market Model with Electric Vehicles) is an experimental agent-based model that analyses how carbon reduction policy in transportation may increase number of Electric Vehicles and how does that would influence on the electricity price. Agents are ESCOs (Energy Service Providers) which can distribute fuels and their objective is to maximize their profit.

In this paper, EMMEV is used to analyze the impacts of the LCFS (Low Carbon Fuel Standard), a performance-based policy instrument, on electricity prices and EV sales. The agents in EMMEV/regulated parties in LCFS should meet a certain CI (Carbon Intensity) target for their distributed fuel. In case, they cannot meet the target, they should buy credit to compensate for their shortfall and if they exceed, they can sell their excess. The results, considering the assumptions and limitations of the model, show that the banking strategy of the agents contributing in the LCFS might have negative impact on penetration of EVs, unless there is a regular Credit Clearance to trade credits. It is also shown that the

electricity price as result of implementing the LCFS and increasing number of EVs has increased between 2-3 percent depending on banking strategy.

Keywords: low carbon fuel standard; electric vehicles; policy analysis; electricity market; agent based modelling

1. Introduction

The most important global agreement addressing climate change was signed in Paris in 2016 under the United Nations Framework Convention on Climate Change ([UNFCCC](#)) dealing with the mitigation of GHG (Greenhouse Gas) emissions, adaptation and financing starting in the year 2020. This agreement indicates the global commitment (195 countries signed the Paris Agreement) to address the severe global consequences related to climate change. By means of this agreement, the global average temperature should be held below 2 °C and a pathway for greenhouse gas (GHG) emissions and climate-resilient development should be designed ([UNFCCC 2016](#)).

Almost a quarter (23 percent) of global energy related GHG emissions are from the transport sector ([IEA 2009](#)) and it is the fastest growing sector for emissions ([Kahn Ribeiro, Kobayashi et al. 2007](#)). In addition, around 35 percent of the fossil fuels in the world are consumed in the transport sector ([IEA 2016](#)). Therefore, design and implementation of transportation policies to decrease emissions is of high importance in order to comply with the Paris Agreement ([Burleson 2016](#)).

Sustainable transportation and the electrification of the transportation sector are highly interrelated and it is shown that in general, electrification of transport can lead to lower carbon emissions in transportation ([Eberle and von Helmolt 2010](#)). On the other hand, support schemes promoting different sustainable transportation is preferable to be local and based on Life Cycle Analysis (LCA). In [Fazeli and Leal \(2011\)](#), based on LCA, it is shown that in most of the cases electrification of the transport sector can lead to lower carbon emissions. Based on the above studies, it is assumed in this paper that the electrification of the transport sector can lead to lower emissions.

Electric mobility support programs include policies that subsidize the higher purchase price of Electric Vehicles (EVs) and promote the installation of charging infrastructure ([European Automobile Manufacturers Association 2013](#)) ([Sierchula, Bakker et al. 2014](#)). These policies will eventually increase the number of EVs on the roads and increase electricity consumption ([Karnama 2009](#)) ([Lopes, Soares et al. 2009](#)) and will impact electricity markets as single platforms for electricity trade. This research contributes to the field by increasing the understanding of the intersection between electric mobility programs and the electricity market.

The main objective of this paper is to bring understanding on how Low Carbon Fuel Standard (LCFS), a performance-based policy instrument to accelerate transition to low-carbon fuel in transportation, can influence the structure and prices of the electricity market as well as EV sales. This paper will describe what are the impacts of LCFS on the electricity market and how this introduction of LCFS may affect electricity prices and EV sales. These are done by modelling LCFS and electricity market and the hypothesis of the model is that sustainable transportation support policies will increase number of electric vehicles and this will increase demand for electricity which it is expected to increase the electricity price ([Hadley and Tsvetkova 2009](#)).

EMMEV stands for Electricity Market Model with Electric Vehicles and is an agent-based model developed by the authors to study the above research questions. In this paper, Electric Vehicles are referred to vehicles with grid charging capability including Plug-in Hybrid Electric Vehicles and Battery Electric Vehicles. EMMEV is a platform for testing different policies for increasing the number of Electric Vehicles and charging infrastructure. Throughout this paper, the LCFS is chosen as a low-carbon transportation support policy in order to investigate the impact on electricity price and EV sales.

The Low Carbon Fuel Standard (LCFS) ([Yeh, Sperling et al. 2012](#)) is one of the regulatory measures for increasing the share of low carbon fuels in the transportation sector. The LCFS regulates the fossil carbon content of different fuels to reduce carbon emissions. It is a performance-based policy which aims to decrease the CI (Carbon Intensity) of transportation fuels. This has been implemented in California. For a description and discussion of its implementation please see [Farrell and Sperling \(2007\)](#) and [Yeh, Sperling et al. \(2012\)](#).

In this paper, first the main concepts related to EMMEV are described. Thereafter the structure of EMMEV is explained. A test system for testing the impact of the LCFS on the electricity market is introduced in section 4. The results and discussions are presented in section 5. Finally, in section 6, a summary and conclusions are presented.

2. Background and review of relevant concepts

The EMMEV (Electricity Market with Electric Vehicles) consists of two sub-models. The first sub-model is the electricity market model and the second is a model for the Low Carbon Fuel Standard. In this section, the two sub-models are described.

2.1. Electricity Market

Electricity is a commodity that doesn't behave like regular commodities ([Barouti and D. Hoang 2011](#)). The first difference is, unlike other commodities, electricity cannot be stored and needs to be consumed as it is produced. Secondly, the supply at each time needs to exactly meet the demand. The third difference is that the (relatively small scale) storage capability and transfer of electricity is subject to major losses. All abovementioned differences have made the structure of the electricity market unique since traders cannot store a large percentage of the commodity.

There is a forth difference which makes the trading structure of the electricity even more unique: electricity is becoming a dominant energy carrier and is entering other energy sectors such as transportation ([van Stralen, Uslu et al. 2013](#)). Thus, there might be mutual influences between the electricity market structure and transportation policies.

An electricity market is a market for trading electricity and related services. The market is mainly cleared at partial time spans (mainly one hour) and all the regulated parties are subjected to the same price. The regulated parties in the market are generation units which need to bid into the market the amount of energy that they can generate for each hour and their price per unit of energy. On the other hand, there are retailers who buy electricity on an hourly basis. The demand is usually quite inelastic, however, new regulations and products

(such as load disaggregation products) are designed to increase the responsiveness and bring flexibility to the demand side ([Biggar and Hesamzadeh 2014](#)).

In order to guarantee a secure supply of electricity, there are three markets with different time regimes within the electricity market; the spot market, power regulation and the automatic reserve ([Albrecht, Nilsson et al. 2012](#)). The spot market (also called load settlement) is an hourly price settlement which leads to a uniform price for all regulated parties in a specific area. The additional balancing requirements which cannot be met in the spot market, due to unexpected demand changes within an hour, are regulated in the power regulation market. This occurs within minutes or seconds. The automatic reserve serves the need to balance the demand and supply within fractions of a second. There are some generation units with very fast response times which can enter this mode and balance the load very quickly ([Albrecht, Nilsson et al. 2012](#)) ([Biggar and Hesamzadeh 2014](#)). In this paper, the spot market of the electricity market is modelled in the first sub-model within EMMEV.

2.2. Low Carbon Fuel Standard

The transition to low-carbon transportation fuels is becoming increasingly important and needs a fast change. However, introduction of low carbon fuels in transportation is hindered by limitations and problems including reduced investments, barriers in technology development and energy industries ([Foxon 2002](#)), other forms of technological and market inertia delaying investments in deployment and R&D ([Seto, Davis et al. 2016](#)), cartel pricing, and the failure of markets to assign a price to greenhouse gas (GHG) emissions ([Yeh, Sperling et al. 2012](#)).

Various policies are adopted to overcome these market failures and barriers, ranging from regulatory measures, such as emissions regulations and fuel economy standards, to financial levers such as tax reductions, rebates and feebate schemes ([Greene, Patterson et al. 2005](#)). There are other policies such as waivers for parking places and tolls, and specifying separate driving lanes for EV drivers. Each has different advantages and disadvantages ([Sprei and Bauner 2011](#)) ([Mersky, Sprei et al. 2016](#)).

Among the regulatory measures, the LCFS is a performance-based policy designed to accelerate the transition to low-carbon transportation fuels by stimulating innovation and investment in new fuels and technologies. The LCFS aims to provide a durable policy framework that will stimulate innovation and technological development. Since 2007, the LCFS policy has been adopted in California, Oregon, the European Union (Fuel Quality Directive, FQD), and British Columbia (Renewable and Low- Carbon Fuel Requirement Regulation, RLCFRR) ([Lade and Lin Lawell 2015](#)) ([Yeh and Witcover 2013](#)) ([Yeh and Witcover 2014](#)).

The LCFS is based on credit trading, with the intent of harnessing market forces and providing industry with flexibility to optimize their incentives. To assure that emissions are regulated effectively life-cycle measurements of GHG emissions are used.

The LCFS is a hybrid of a regulatory and market policy instrument. It does not include mandates for any fuel or technology and as such does not attempt to pick winners or losers. Instead, it defines an average emissions intensity standard—measured in grams CO₂

equivalent per mega-joule of fuel energy (gCO₂e/MJ)—that all energy providers must achieve across all fuels they provide. Many options exist for meeting the standard. Regulated parties are free to employ any combination of strategies that suits their circumstances and perspectives—including the purchase of credits from other companies.

There is a similar instrument to the LCFS concerning renewable electricity generation called the Renewables Certificate Market (RCM). RCM was implemented in 2002 through the RPS (Renewable Portfolio Standard) in California ([Berry and Jaccard 2001](#)) as well as in Sweden in 2003 called ‘elcertifikatmarknad’. Norway joined Sweden in 2012 and they created the ‘nordiska elcertifikatmarknad’ ([Fagiani, Barquín et al. 2013](#)). The main goal of this market is to promote electricity generation from renewable resources ([Tudor 2012](#)) ([Nilsson 2012](#)). RCM has been compared with the LCFS in Table 1.

Table 1 Comparison of LCFS and Renewables Certificate Market

Market	Main goal	Players	Certificate receivers	Quota obligation
RCM	Promote renewable electricity generation	Electricity generation units and large electricity consumers and electricity retailers	one certificate for each MWh of electricity generated from renewable resources	one quota obligation for some percentage of electricity consumption
LCFS	Promote low-carbon transportation fuels	Energy providers for transportation	one credit for CI reduction below decreasing annual targets	one credit for sales of fuel with higher CI than LCFS annual target

Both the LCFS and RCM aim to reduce GHG emissions. The target of RCM is the electricity generation sector while the LCFS aims to reduce GHG emissions in the transportation sector. The regulated parties in RCM are generation units and the electricity consumers. However, in the LCFS, the regulated parties are fuel distributors in the transportation sector.

In the RCM, each regulated party can receive one certificate for each MWh of electricity generated from renewable resources. Certain electricity consumers and electricity retailers are obliged to buy certificates based on the amount of electricity they consume. In the LCFS, the regulated parties can sell more low-carbon fuels, or purchase LCFS credits from other regulated parties, low carbon fuel producers, or other regulated parties. The LCFS defines an average emissions intensity standard that all energy providers must achieve across all fuels they provide.

2.2.1. Operation of Low Carbon Fuel Standard

The compositions of the fleet (gasoline, diesel or electric vehicles) and how fast the market can make a transition to alternative fuels/vehicle technologies determine the market share of the fuel. The LCFS provides incentives for fuels with lower intensities, but does not guarantee a higher (or the highest) market share. In the California the LCFS, the target is a 10% reduction in overall CI by 2020 ([Air Resources Board - California 2016](#)).

In each year, the regulated parties in LCFS must meet certain CI target for the fuel they are distributing. In case the regulated parties cannot meet their target, they need to buy credits. On the other hand, if the regulated parties exceed the target, they can sell their credit.

The structure and mechanism for credit trade in LCFS is described in the next sections ([oregon.gov 2010](http://oregon.gov)) ([Air Resources Board - California 2012](#)).

All companies which provide fuel to end users in the transportation sector can choose to be regulated parties in the LCFS. The only obligated regulated parties in the LCFS are baseline fuel producers, i.e. petroleum fuel providers. All regulated parties are indirectly mandated to reduce GHG emissions by reforming their fuel supply. In EMMEV it is assumed that the regulated parties are biofuel providers, gasoline providers and ESCos (Energy Service Companies) which provides EV aggregation services. When it comes to EV aggregation services, utilities and ESCos have the same behaviors.

2.2.2. Calculation of credit/deficit

The LCFS credits are calculated based on a Low Carbon Fuel Standard defined by regulators each year and expressed in gCO₂e/MJ. All the regulated parties are evaluated based on a target to be eligible to get the LCFS credits (have credit) or obliged to buy the LCFS credits (have deficit). In order to calculate number of the LCFS credits each regulated party receives, the following steps should be followed ([oregon.gov 2010](http://oregon.gov)). First, the energy (MJ) of the sold transportation fuel by each regulated party is calculated. The conversion factors from liter (in case of liquid fuels) or kWh (in case of electricity fuel) are available by regulators. MJ of each fuel is calculated as following:

$$\text{Litre of sold fuel} \times \text{Energy Density (MJ/Litre)} = \text{MJ}$$

and for EVs:

$$\text{kWh of electricity} \times \text{Energy Density (MJ/kWh)} = \text{MJ}$$

In the second step, the EER (Energy Economy Ratio) is considered. EER aims to account for differences in energy efficiency for vehicles. EER for gasoline is 1 and 3.4 for electric vehicles since the electric engine is more efficient than the combustion engine.

The third step is to calculate the difference between the LCFS target of each specific year and the CI of the fuel sold. If the regulated party has not met its CI target, it is producing deficit and is obliged to buy the LCFS credit. In case of exceeding the target, the regulated party is producing credit and is eligible to receive the LCFS credit.

The fourth and last step is to convert the credit/deficit into grams of CO₂ equivalent. Credit/deficit are expressed in terms of greenhouse gas emissions volumes, where credits indicate the emissions *saved* by selling a low carbon fuel compared to selling a fuel that exactly meets the low carbon fuel standard for that year. The tons of CO₂ are calculated as following:

$$\text{MJ} \times \text{EER} \times \text{CI difference (gCO}_2\text{E/MJ)} \times 10^{-6} = \text{credit or deficit generated}$$

The final number shows the number of deficit/credit that each regulated party will get for the fuel sold at each year.

2.2.3. *Electricity in the LCFS*

In California, under the new regulations, new regulated parties are introduced in the market in which electricity used as a transportation fuel can generate the LCFS credits. These regulated parties are Electric Vehicle Service Providers (EVSP) for public charging, Electric Vehicle (EV) fleet operators, battery switch station owners, site hosts of private access EV charging equipment at businesses or workplace, transit agencies operating a fixed guideway system or electric buses and the Electrical Distribution System Operators (DSO) for residential charging. These regulated parties, in general, are the ESCo which are in charge of EVs charging and providing EV charging services ([Air Resources Board - California 2016](#)). Utilities and ESCos have the same behaviors when they provide EV aggregation services.

Low-carbon fuels that meet the CI target of 2020 are exempted from the LCFS. This means that entities that are providers of these fuels do not have obligations under the LCFS and can thus choose not to join the LCFS program. However, if they decide to participate in the LCFS, they can gain the LCFS credits and trade it in the structure of the LCFS ([Air Resources Board - California 2016](#)). In EMMEV, it is assumed that the agents with electricity as fuel for transportation decide to participate in the LCFS.

2.2.4. *Trading in the LCFS*

At the end of a compliance period (one year for most of the LCFS programs), each regulated party must retire a sufficient number of credits to meet the obligation of the compliance period. The regulator normally sets a maximum price at the beginning of each year (\$200 for each credit in California) ([Air Resources Board - California 2012](#)). The regulated parties in the LCFS can trade their LCFS credits in one of the following markets:

- Ongoing LCFS Credit Market
- Credit Clearance Market

In the ongoing LCFS Credit Market the regulated parties can trade their credits through bilateral contracts any time during the compliance period. This is similar to a forward contract in the electricity market ([Green 1999](#)). There is normally a low risk in those contracts.

If the regulated parties don't have contracts in the ongoing LCFS Credit Market or there are overall credit shortfalls and the regulated parties reported net credit deficits at the end of the reporting period, the regulator will set up a clearance market to enforce the selling and trading of credits for regulated parties. Credits acquired for this purpose are defined as "Clearance Market" credits ([Air Resources Board - California 2012](#)) ([Air Resources Board - California 2016](#)). The Credit Clearance Market doesn't happen frequently; if all parties are complying, there is no need for it.

3. What is EMMEV?

EMMEV is an agent-based model developed to analyze the effects of low-carbon transportation policies on the electricity market. In this paper, EMMEV is used to study the effects of the LCFS on the electricity market. The agents are ESCos (Energy Service Companies) and it is assumed that the ESCos in EMMEV can provide power generation, electricity retailing and EV aggregation as energy services. When it comes to EV aggregation services and retailing, utilities and ESCos have the same behaviors. Regarding power generation, there are exception cases where ESCos own small power generation units but utilities are the ones which can own and operate larger generation units.

3.1. About modelling

Modelling is the art of simplification to describe a limited part of our complex nature (or a socio-technical system). Models support researchers and generally human-beings to overcome our limited success in understanding our complex nature.

Relative to human's understanding, nature is extremely complex. This complexity is known to human beings from very early ages. Therefore, there is no other way than relying on modelling to give study the incidents in the nature. This is done in two ways; statistics or dynamics ([Morrison 2012](#)).

Statistics is well established for modelling while dynamics despite of its older history, is less mature regarding model development, since it requires more computational capability that has only more recently been available ([Morrison 2012](#)) ([Benth, Benth et al. 2008](#)). In this paper, a socio-technical system in the intersection of the LCFS and electricity market is modelled using agent-based modelling (to be described in the next section).

3.2. Agent-based modelling

The modeling tool used in this paper is an agent-based model (ABM) ([Parsons and Wooldridge 2002](#)) ([Ringler, Keles et al. 2016](#)). An ABM is composed of several agents. The agents can have the inherent properties of flexible autonomy, re-activity, pro-activeness and social ability. ([McArthur, Davidson et al. 2007](#)) ([Wooldridge 2009](#)).

ABM can be considered under the more generic terms of Multi-Agent Systems (MAS) which simply describe various computational instruments following an agent-based approach ([Wooldridge 2009](#)). MAS comprises also the domain of (distributed) artificial intelligence and agent-based control systems which aim to design autonomous (software) agents and implement them in real-world cases (in the sense of designing and configuring systems in practice). In contrast, ABM specifically deals with the computational representation of Complex Adaptive Systems within their boundaries. ABM is also used for studying economically motivated relationships also known as agent-based computational economics (ACE) ([Ringler, Keles et al. 2016](#)) which is the main focus in this paper.

3.3. EMMEV: an agent-based model

As mentioned above, EMMEV consists of two sub-models: the electricity market model and the Low Carbon Fuel Standard model. There are two layers in the model; first the agent layer which is the core of the modelling and a geographical layer which addresses different geographical locations for different case studies. EMMEV studies the interactions of agents for 15 consecutive years (2016-2030). Regardless of all the number of languages, frameworks, developed environments, and platforms published during the last decade in the literature, implementing Agent-based Modelling is still a complex task, which in general is coded by using middleware as RePast ([Collier and North 2012](#)). The RePast system is a Java-based middleware for the development of trivial agent platform and agent models. It was developed at the University of Chicago's Social Science Research Computing division and is derived from the Swarm simulation toolkit. RePast offers a set of reusable Java Bean components, along with several flexible interconnection methods to combine those components and thus create software agents. Furthermore, RePast uses the base of the Knowledge Query and Manipulation Language (KQML) to promote communications among agents inside the platform. KQML provides the bases for the most widely used agent communication language (ACL), and over the last years it has been extended, modified, and standardized by Foundation Intelligent Physical Agents (FIPA) ([Suguri 1999](#)). Agents use KQML to send performatives to indicate the action that another agent should take on its behalf. Another major meaning of the KQML is the use of ontologies to ensure that two agents communicating in the same language can correctly interpret statements in that language. The main reason for the choice of RePast is due to the Java Bean technology, which have allowed new computational features to developers to reap the benefits of rapid application development in Java by assembling predefined software components.

The agents in the model are ESCOs and they are profit maximizing entities. The profit for each agent is calculated as below:

$$P_{ESCO} = R_{ESCO} - C_{ESCO}$$

The revenue of each ESCo has three sources:

$$R_{ESCO} = R_{Generation} + R_{Retailing} + R_{EV\ aggregation} + R_{LCFS}$$

The revenue from generation is set by the spot price of electricity and the amount of generated electricity. The revenue from retailing is also dependent on the price scheme offered to the end consumers and the amount of consumption at each hour. The EV aggregation is the revenue from the sale of electricity to EV owners. The agents can make different profits by offering different price patterns to EV owners. The ESCOs will have some revenue from the LCFS market by selling their LCFS credit. The costs associated to ESCOs are defined as following:

$$C_{ESCO} = C_{Generation} + C_{Retailing} + C_{EV\ aggregation} + C_{LCFS}$$

The electricity generation costs, cost for buying electricity for retailing and cost for buying electricity for EVs are the main costs of ESCos. The agents are assumed to be independent entities which deal with each other under the same condition in the electricity market and the LCFS market.

It is also assumed that the agents interact with each other in a market environment based on the following four rules:

1. The agents provide the same service
2. All agents are price takers - they cannot control the market price unless by banking strategy
3. All agents have a relatively balanced market share
4. Users have complete information about the service

The agents have the possibility to bank the credits which they received from the LCFS ([Yeh, Sperling et al. 2012](#)). Based on these two scenarios are created. In the first scenario, it is assumed that all the agents are cash constrained which means that they sell their credit by the end of each year to generate cash to operate their business. The second scenario is the case in which agent number 2 (one randomly chosen agent) banks the credits and sells them every 5 years under the assumption that they will influence the market, increase prices and gain more profit. This might not happen in real world with a well-functioning LCFS. However, in case the program is not well designed, then the described shortfall might occur. One of the solutions to avoid this scenario could be to define a limit on how much credits each market play can bank in each specific time or controlling credit liquidity in the market.

Agents which are eligible to receive credits in the LCFS market, can sell their credits and gain some profit. In EMMEV, this profit is meant to be spent on the charging infrastructure and subsidize the sales of EVs. In [Sierzechula, Bakker et al. \(2014\)](#), it is claimed that each 900 € (\$1000) increase in financial incentives would cause a country's EV market share to increase by 0.06%. However, the investment in charging infrastructure could be more beneficial to increase the number of EVs; each additional station per 100,000 residents would increase its EV market share by 0.12% ([Sierzechula, Bakker et al. 2014](#)) and this has been used as elasticity in this research. In this paper, EMMEV is tested by assuming that the profit from the LCFS are spent in charging infrastructure. In future, EMMEV can be used to investigate different other scenarios such as spending LCFS revenue for rebates for EVs.

In each of the three revenue cases (generation, retailing and EV aggregation and LCFS), the agents interact differently. In Figure 1, the interaction of agents in generation is shown.

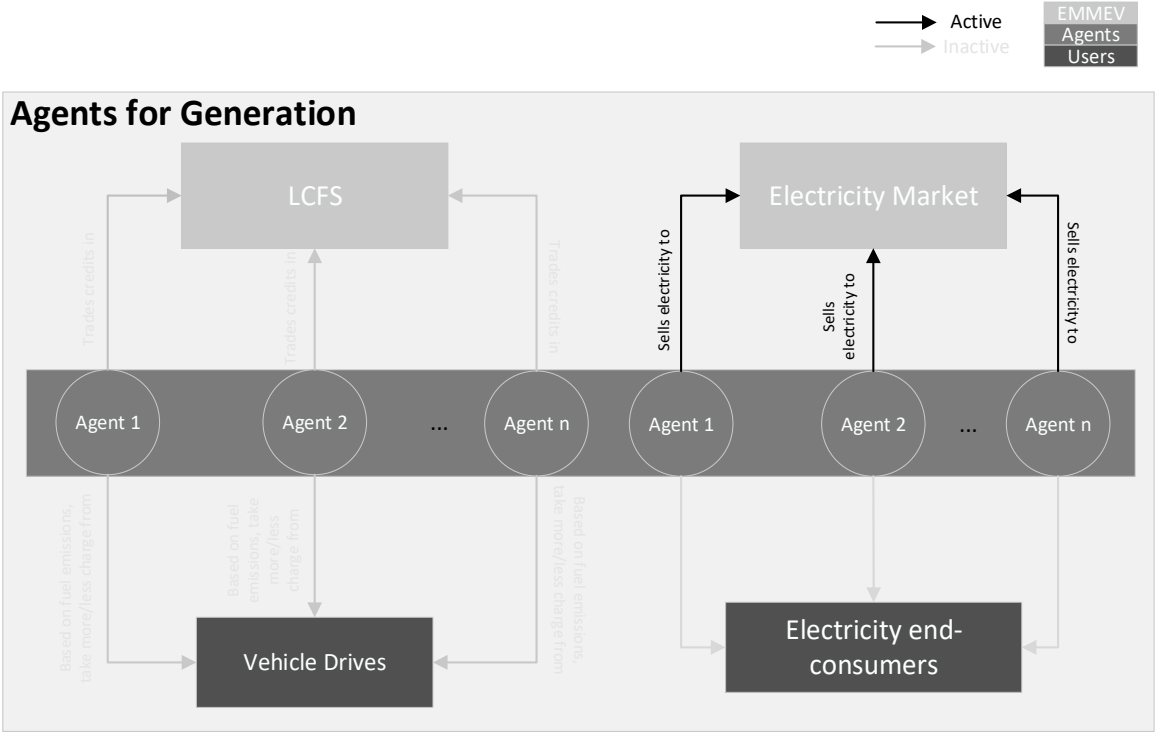


Fig 1 Agents interaction for generation in electricity market

As shown in the above figure, the agents sell their generated electricity in the electricity market. It is assumed that the agents have balanced share of market and cannot influence prices. The electricity prices are set by passing demand curve through the generation curve at each hour.

Retailing and EV aggregation create similar agents’ interactions as it is shown in Figure 2.

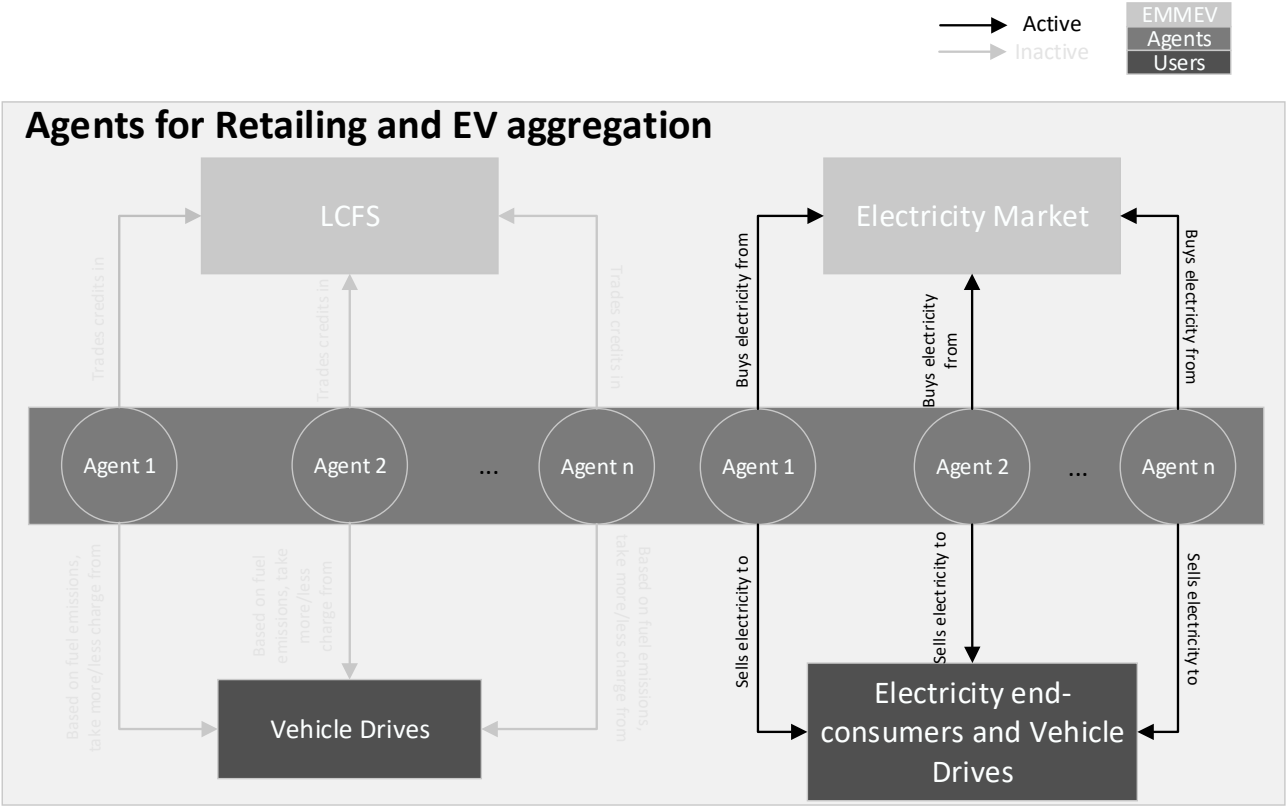


Fig 2 Agents interaction for retailing in electricity market

In this energy service, the agents buy their electricity from the electricity market and sell it to the end users. This is valid for the electricity to be sold for any industrial, commercial and residential application as well as for EVs to charge their batteries. The agents also interact in the LCFS part of EMMEV. This has been visualized in Figure 3.

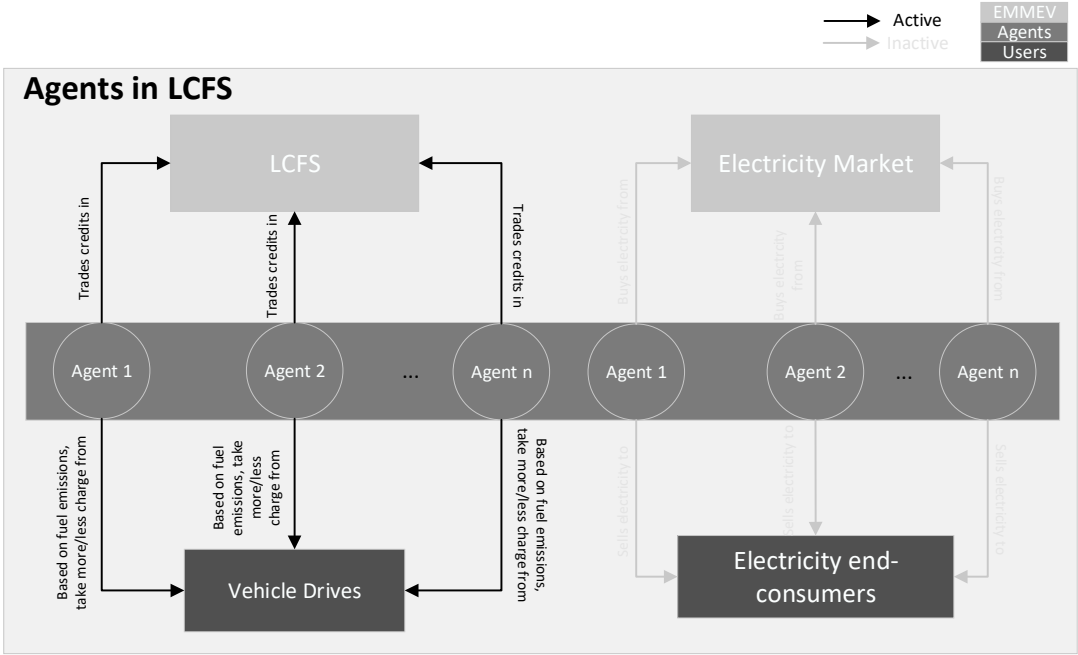


Fig 3 Agents interaction in LCFS

In this service, the agents interact in the LCFS market to trade their credits. The agents also charge the vehicle drivers less or more based on the emissions from each specific fuel sold and the credit they get for each specific fuel.

For simplicity, it is assumed that there is a single electricity market in the model which consist of two countries. By assumption, each country is divided into two regions with different electricity prices due to line congestion between the regions.

Models such as EMMEV create an understanding in this complex, interrelated and multidisciplinary area. This understanding serves the regulators and policy makers to guide the transportation toward low-carbon alternatives.

4. Test system

EMMEV has been tested in a simulated market with two fictitious countries. The population of these countries are assumed to be very similar and both countries have taken serious measures for both renewable electricity generation and e-mobility. In each country, it is assumed that there are two price regions as shown in Figure 4.

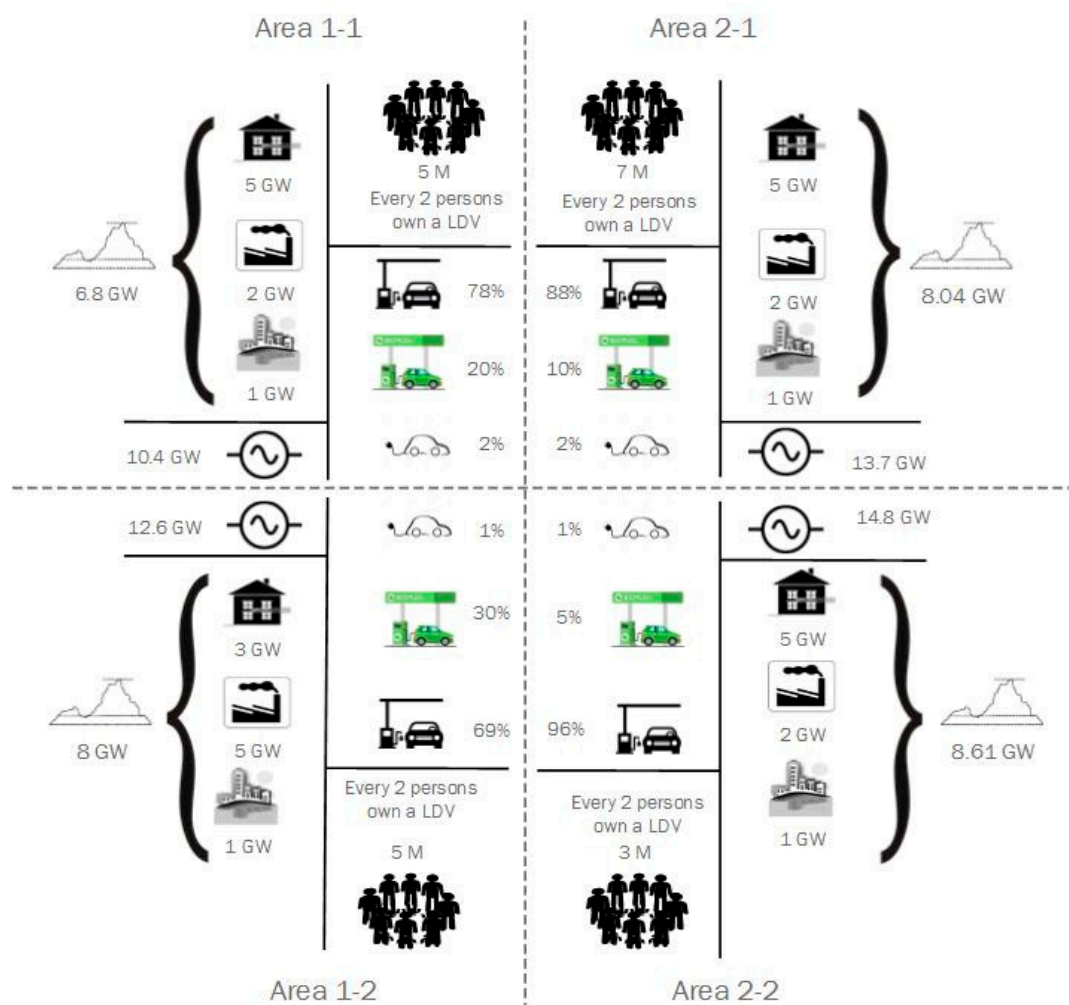


Fig 4 . The test system structure LDV: Light Duty Vehicle

In the figure above, four areas in the electricity market are depicted. In each area, the peak load and how the peak load is divided between residential, industrial and commercial loads are presented. On the lower part for each area, the total generation capacity is shown. Then,

the population and the number of vehicles per person are shown. Finally, the percentage share of each type of vehicle, electric, biofuel or regular gasoline, is depicted for each area.

The parameters used in the test system are described in Table 2. The table is a summary of the parameters used for modelling purpose. It is shown whether each parameter is based an assumption or if it is taken from other references (the reference is shown) or if the parameters is derived from other assumptions or referenced parameters.

Table 2 Description of the parameters in the test system

	General (G)		Electricity consumption (EC)			Electricity generation (EG)		Mobility (M)	
Parameter ID	G1	G2	EC1	EC2	EC3	EG1	EG2	M1	M2
Parameter description	Number of countries in the electricity market	Population in each country	Electricity consumption per person	Peak electricity consumption	Load patterns	Power generation capacity	Share of different type of generation	Number of LDV per person	Share of each type of vehicle
Assumption	√	√	√			√ ¹	√	√	
Based on a reference					√ (Karnama, 2009)				
Derived from another parameter(s)				√ (G2, EC1)		√ (EC2, EC3)			√ (M1)

¹It is assumed that there is always enough extra generation. Therefore, the case of infinite electricity price is impossible to happen in this model.

There are three types of loads in the market: residential, industrial and commercial. It is assumed that all the individual loads follow the same pattern depending on their type as shown in Figure 5.

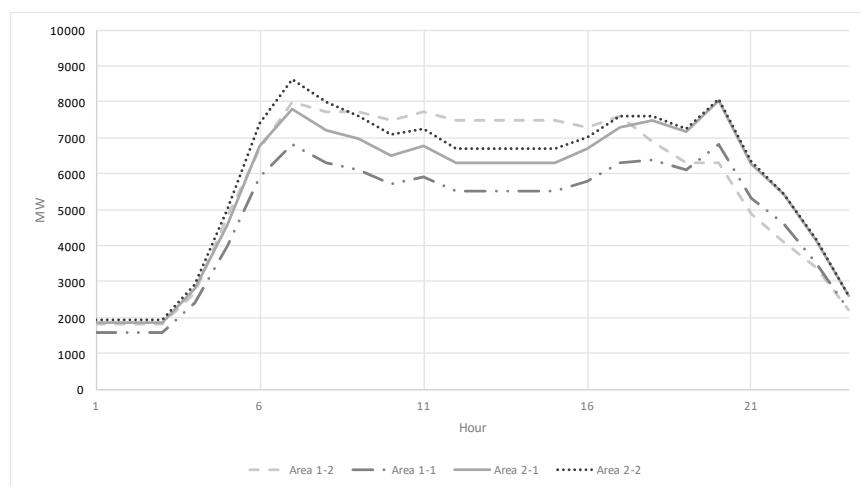


Fig 5. Load in 4 different areas

In the system, there are 5 agents and their market shares are summarized in Table 3.

Table 3 Agents in the test system

Agent number	Generation unit (MW)	Share of Electric Vehicles serviced by each agent (%)
1	7300	26
2	17600	24
3	8100	21
4	12600	4
5	5900	26

The agents are ESCos which can own generation units and provide EV aggregation services. In Figure 4, the size of the generation units owned by each agent is shown. The generation units are of different types: hydro, thermal, solar, and wind generation units. The primary share of the market from EV aggregation services is also shown in the Table 3. This share can be changed by different strategies that each agent can take in the LCFS market.

The EVs in this simulation environment have a battery capacity of 8 kWh with a charging power of 3 kW/h. The battery capacity and charging power are fairly low in comparison with existing electric vehicles. However, due to lower penetration of EVs, this can be still a valid assumption ([Karnama, Resende et al. 2011](#)).

There are three fuel types in the test system are described in Table 4.

Table 4 Fuel alternatives in the test system

Fuel type	gCO ₂ /MJ	EER	Primary Fuel share
Electricity	20	3.4	1.58
Biofuel	40	1	18.65
Diesel/Gasoline	98	1	79.77

The target is to decrease emissions from transportation by 10% by the end of 2030 starting from 2016. Based on this target, the number of electric vehicles which are needed to reach that target is set. LCFS is set to reach a target and EMMEV has been studied how effectively LCFS can reach that target. The increase in number of EVs will eventually influence the electricity price. The process in which EMMEV follows to get the outputs are visualized in Figure 6.

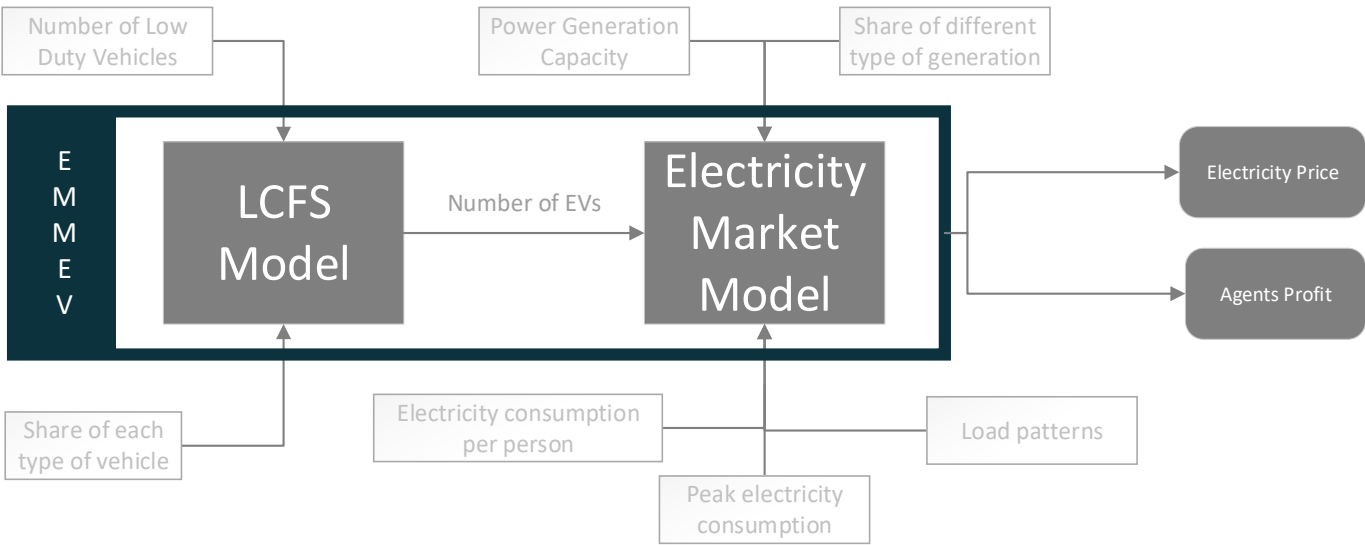


Fig 6 EMMEV Process

In this process, the number of EVs, the output from the LCFS model, is an input to electricity market. Therefore, the number of EVs will influence the electricity price which is discussed and analyzed in the next section of this paper.

5. Results and discussions

The agents can sell their credits in the Ongoing Credit Market or Credit Clearing Market as described in section 2. If regulated parties don't have contracts in the ongoing LCFS Credit Market or there are overall credit shortfalls and the regulated parties reported net credit deficits at the end of the reporting period, then a Credit Clearing Market will occur. Therefore, it is assumed that all the credits are sold in the Ongoing Credit Market.

As described above, the regulators in the LCFS program, set a maximum price for credits each year. This price will increase each year based on inflation and other economic parameters ([Air Resources Board - California 2012](#)). As shown in Figure 4, the initial percentage of EVs in each area is between 1-2 percent and the total EV penetration is 1.58 percent. As shown in Figure 7, the price of credits increases between 0 to 5.5 percent and the final penetration of EVs (in percent) is depicted.

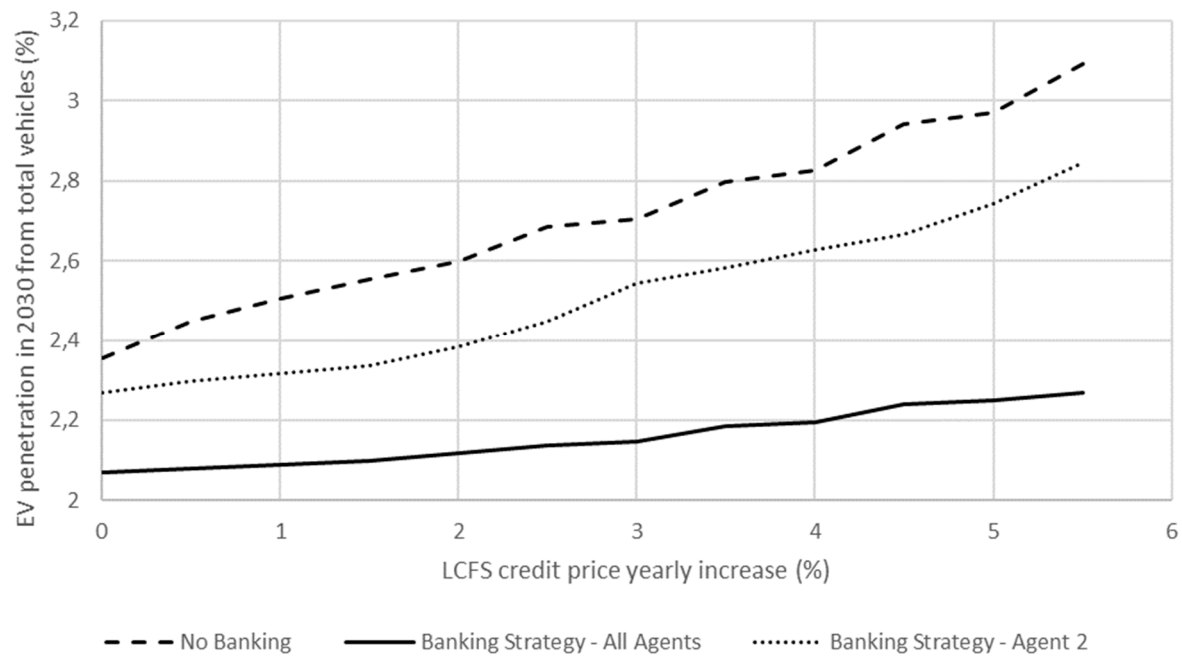


Fig 7. Impact of LCFS credit prices increase on EV penetration

In the above figure, banking strategy is shown to have a negative influence on EV penetration. This is because the market is not cleared often enough to give enough liquidity of credits to increase EV penetration. The more agents bank their credits, the lower the liquidity reducing the penetration rate of EVs.

In the LCFS market, the agents mainly trade their credits in the ongoing LCFS credit market which is a forward market with bilateral agreements. As a drawback to EMMEV and in general in LCFS, the Credit Clearance Market happens rarely since this requires a widespread market (which is not the case in EMMEV) and if that happens more frequently, it will help the credit price competitiveness and more competition among the agents.

5.1. Electricity prices

The electricity prices are determined by crossing the electricity demand curve with the electricity supply curve in each area. Electricity prices without any EVs in the system are shown in Figure 8.

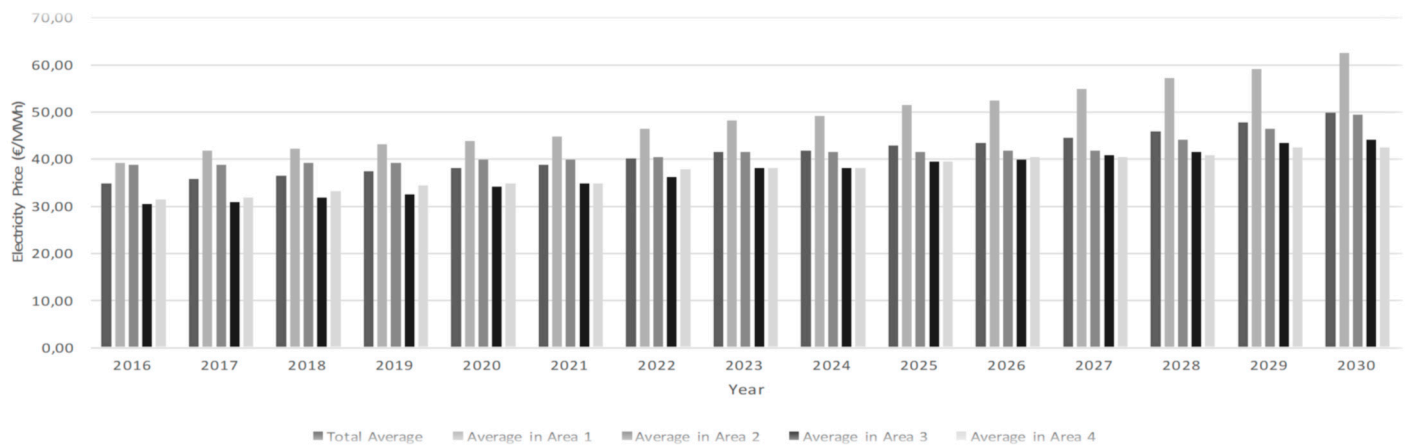


Fig 8. Average electricity prices in four areas and average in all areas from 2016 till 2030

As it can be seen above, the electricity price in EMMEV increases linearly when the consumption increases. It is assumed that the generation units will keep their capacity during the period that EMMEV is modelled and there is always enough generation for the demand. In Figure 9 the changes in electricity prices as result of the LCFS, are shown.

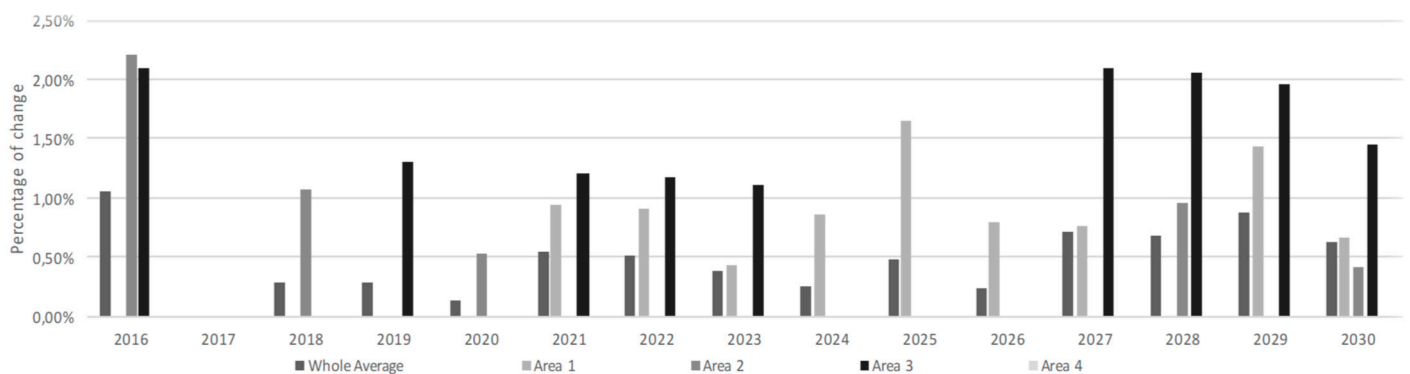


Fig 9. Changes of electricity prices (%) with EVs and LCFS (no banking)

As can be seen the electricity price increases on average by 1-2 percent per year. In the next figure, the changes of electricity prices as result of the LCFS with agents implementing a banking strategy are shown.

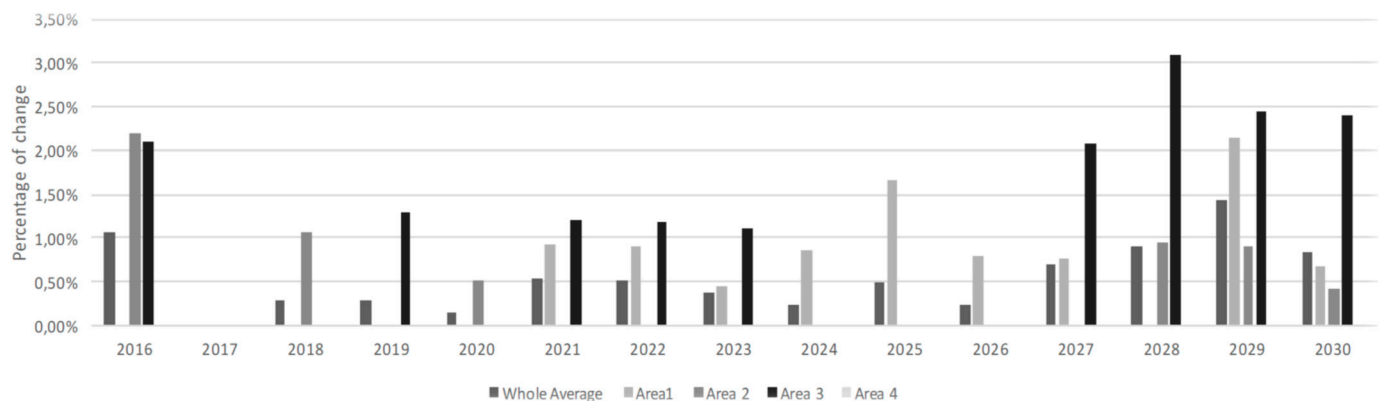


Fig 10. Change in electricity price (%) with EVs and LCFS (with banking)

The size of electricity consumption by EVs in comparison to the overall electricity consumption is very low. That’s why the electricity price increase is less than 2% in all the areas because of the implementation of the LCFS. In addition, the size of the EV fleet does not change considerably through the implementation of the LCFS.

The electricity price changes are dependent on both demand and supply. As the electricity supply function is a step function, an increase in demand can increase or keep the electricity price levelled as can be seen in Figure 9.

The banking strategy has a small negative impact on number of EVs and consequently on electricity prices as shown in Figure 10. The electricity prices changed more in the banking strategy case to the no banking strategy case. The percentage of change in electricity price between banking and no banking strategy is very low. The low share of the total electricity consumption by EVs is the main reason. The average year to year change in electricity price is 0.47% in the no banking case and 0.54% in the banking case.

The sensitivity analysis is described in Table 5.

Table 5 Sensitivity analysis of variables									
Parameter	Number of countries in the electricity market	Population in each country	Electricity consumption per person	Peak electricity consumption	Load patterns	Power generation capacity	Share of different type of generation	Number of LDV per person	Share of each type of vehicle
Sensitivity of EV penetration in 2030 in relation to	Neutral	Linear proportional	Neutral	Low	Low	Low	Low	High	High
Sensitivity of electricity price in relation to	Neutral	Linear proportional	High	High	Depends on the pattern	High	High	Neutral	High

These sensitivity analysis is performed by running the model by varying a parameter and keeping all other parameters fixed. The sensitivity results (neutral, linear proportional, high and low) in Table 4 are shown in relative measures to make them comparable with each other. Electricity consumption per person, peak electricity consumption, and share of different types of generation units can influence the penetration of EVs in 2030. On the other hand, number of LDV (Low Duty Vehicles) per person and share of each type of vehicle can have a large influence on electricity prices.

6. Conclusions

The LCFS is a policy with the aim to promote low carbon fuels. In this paper, an agent-based model, called EMMEV is developed to investigate the influence of the LCFS on the number of EVs and on electricity price.

The effectiveness of this policy is mainly dependent on wide geographical spread, resilience of market liquidity and price competitiveness. Based on the assumption that agents reinvest the revenue from the LCFS on EV charging infrastructure or other EV promoting activities such as incentives, the effect of the LCFS on the adoption of low carbon vehicles is quite small, as demonstrated in this paper. Consequently, the impact of an increased number of EVs on electricity prices is not considerable.

In EMMEV, it is assumed that the agents only trade in the Ongoing Market and since the regulated parties have contracts in the ongoing LCFS Credit Market and there are no credit shortfalls. It is also assumed an elasticity of each additional station per 100,000 residents would increase its EV market share by 0.12% and the profit from the LCFS are spent in charging infrastructure (although there are other studies have shown that rebates might be more effective ([Axsen and Kurani 2013](#))). The results from EMMEV show that the impact of the LCFS on EV penetration is low. It is also indicated that the LCFS is not an effective driver for EV penetration in a small geographical area with low liquidity. The LCFS seems to need large regulated parties to guarantee the resiliency required for market liquidity, since supply and demand are dependent on a larger number of participants.

Market liquidity is one of the important factors for financial stability and real trade activity in the LCFS. Low market liquidity downgrades the efficiency of the market ([Christensen and Hobbs 2016](#)) but is also is the result of inefficient design of the market. The regulators should follow the market changes every year to target a right level and adapt the supply and demand of credits to ensure trade activities in the market. In case of low market liquidity, the LCFS will be fragile and likely to evaporate in response to shocks. As described above, LCFS can be effective when the market is spread in wide geographical area to ensure enough credits in the market. The credit prices will also become less unpredictable in case of higher market liquidity. Highly uncertain prices will decrease participation of fuel distributors in the market and will make it hard for investors to make long-term decisions.

The price competitiveness in the LCFS is dependent on more regular Credit Clearing Markets. Bilateral contracts will not give enough confidence to investors to be ensured that they can sell their credits and have credible predictions of the credit price. On the other hand, those agents who have not met their previous year-end obligation, can use Credit Clearing Markets to provide additional compliance flexibility. The results from this paper show that the banking strategy of the agents contributing to the LCFS can have a small negative impact on penetration of EVs, unless there is regular Credit Clearance. A regular Credit Clearance can neutralize the effect of banking by providing buyers and sellers flexibility to negotiate mutually beneficial transactions.

From the electricity market perspective, the initial influence of EVs penetration on electricity prices is low. The electricity price in both the banking and no banking case did not change much. Even in case of high EV penetration, the influence on electricity price is not considerable ([Karnama 2009](#)).

As with many policies the design and context of implementation of the LCFS will have an influence on its performance. We have shown, in a simplistic model that in a small market without credit clearance some agents might choose to bank their credits leading to a lower EV penetration rate than what could otherwise be expected.

The interdependence of transportation policies and the electricity market is increasing due to increasing number of Electric Vehicles while these two historically had low interdependence. This paper both introduced EMMEV and also started the investigation of impact of LCFS on electricity market. In the future, EMMEV will be used to investigate the impact of other low-carbon policies on the electricity market.

Acknowledgement

The authors would like to thank Ween Energy AB in Sweden for sponsoring this research. In addition, the authors would like to thank Faculty of Engineering University of Porto, MIT Portugal program and Federal University of Santa Catarina (UFSC) for supporting this research.

References

- Air Resources Board - California (2012). Low Carbon Fuel Standard - Final Regulation Order, Air Resources Board - California.
- Air Resources Board - California (2016). "Low Carbon Fuel Standard." Retrieved 05 August, 2016, from <http://www.arb.ca.gov/fuels/lcfs/lcfs.htm>.
- Air Resources Board - California (2016). Low Carbon Fuel Standard Regulatory Guidance 16-04 - LCFS Electricity Program FAQs.
- Albrecht, M., et al. (2012). "Electrification of vehicles—policy drivers and impacts in two scenarios."
- Axsen, J. and K. S. Kurani (2013). "Hybrid, plug-in hybrid, or electric—What do car buyers want?" *Energy Policy* **61**: 532-543.
- Barouti, M. and V. D. D. Hoang (2011). Electricity as a Commodity.
- Benth, F. E., et al. (2008). *Stochastic modelling of electricity and related markets*, World Scientific.
- Berry, T. and M. Jaccard (2001). "The renewable portfolio standard:: design considerations and an implementation survey." *Energy Policy* **29**(4): 263-277.
- Biggar, D. R. and M. R. Hesamzadeh (2014). *The economics of electricity markets*, John Wiley & Sons.
- Burleson, E. (2016). "Paris agreement and consensus to address climate challenge." *ASIL INSIGHT*, *Forthcoming*.
- Christensen, A. and B. Hobbs (2016). "A model of state and federal biofuel policy: Feasibility assessment of the California Low Carbon Fuel Standard." *Applied Energy* **169**: 799-812.
- Collier, N. and M. North (2012). RePast Java Getting Started, RePast Development Team.
- Eberle, U. and R. von Helmolt (2010). "Sustainable transportation based on electric vehicle concepts: a brief overview." *Energy & Environmental Science* **3**(6): 689-699.
- European Automobile Manufacturers Association (2013). "Overview of CO₂-based motor vehicle taxes in the EU." **4**.
- Fagiani, R., et al. (2013). "Risk-based assessment of the cost-efficiency and the effectivity of renewable energy support schemes: Certificate markets versus feed-in tariffs." *Energy Policy* **55**(0): 648-661.
- Farrell, A. E. and D. Sperling (2007). "A low-carbon fuel standard for California, Part 1: Technical analysis." *Institute of Transportation Studies*.
- Fazeli, R. and V. Leal (2011). "A multi-criteria evaluation framework for alternative light-duty vehicles technologies." *International Journal of Multicriteria Decision Making (IJMCDM)* **Volume 1**: 230 - 251.
- Foxon, T. J. (2002). "Technological and institutional 'lock-in' as a barrier to sustainable innovation." *Imperial College Centre for Policy and Technology Working Paper*.
- Green, R. (1999). "The electricity contract market in England and Wales." *The Journal of Industrial Economics* **47**(1): 107-124.
- Greene, D. L., et al. (2005). "Feebates, rebates and gas-guzzler taxes: a study of incentives for increased fuel economy." *Energy Policy* **33**(6): 757-775.
- Hadley, S. W. and A. A. Tsvetkova (2009). "Potential Impacts of Plug-in Hybrid Electric Vehicles on Regional Power Generation." *The Electricity Journal* **22**(10): 56-68.
- IEA (2016). Global EV Outlook 2016 - Beyond one million electric cars, International Energy Agency.
- IEA, T. (2009). "Energy and CO₂: Moving Toward Sustainability." *International Energy Agency (IEA), Paris, France*.

Kahn Ribeiro, S., et al. (2007). "Transport and its infrastructure. Climate change 2007: mitigation. contribution of working group III to the fourth assessment report of the intergovernmental panel on climate change." Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Karnama, A. (2009). Analysis of integration of plug-in hybrid electric vehicles in the distribution grid. Stockholm, Sweden, Royal Institute of Technology (KTH).

Karnama, A., et al. (2011). Optimal Management of Battery Charging of Electric Vehicles: A New Microgrid Feature. PowerTech, Trondheim, Norway.

Lade, G. E. and C. Y. C. Lin Lawell (2015). "The design and economics of low carbon fuel standards." Research in Transportation Economics **52**: 91-99.

Lopes, J. A. P., et al. (2009). Quantification of technical impacts and environmental benefits of electric vehicles integration on electricity grids. Advanced Electromechanical Motion Systems & Electric Drives Joint Symposium, 2009. ELECTROMOTION 2009. 8th International Symposium on.

McArthur, S. D. J., et al. (2007). "Multi-Agent Systems for Power Engineering Applications; Part I: Concepts, Approaches, and Technical Challenges." Power Systems, IEEE Transactions on **22**(4): 1743-1752.

Mersky, A. C., et al. (2016). "Effectiveness of incentives on electric vehicle adoption in Norway." Transportation Research Part D: Transport and Environment **46**: 56-68.

Morrison, F. (2012). The art of modeling dynamic systems: forecasting for chaos, randomness and determinism, Courier Corporation.

Nilsson, J. (2012). The electricity certificate system 2012 Swedish Energy Agency.

oregon.gov, S. o. O. D. o. E. Q. (2010). Supporting Documentation for Calculating Credits and Deficits - Agenda Item B.

Parsons, S. and M. Wooldridge (2002). Game Theory and Decision Theory in Multi-Agent Systems. Autonomous Agents and Multi-Agent Systems. **5**: 243-254.

Ringler, P., et al. (2016). "Agent-based modelling and simulation of smart electricity grids and markets—A literature review." Renewable and Sustainable Energy Reviews **57**: 205-215.

Seto, K. C., et al. (2016). "Carbon Lock-In: Types, Causes, and Policy Implications." Annual Review of Environment and Resources **41**(1): 425-452.

Sierchula, W., et al. (2014). "The influence of financial incentives and other socio-economic factors on electric vehicle adoption." Energy Policy **68**: 183-194.

Sprei, F. and D. Bauner (2011). Incentives impact on EV markets, Viktoria Institute.

Suguri, H. (1999). A standardization effort for agent technologies: The foundation for intelligent physical agents and its activities. Systems Sciences, 1999. HICSS-32. Proceedings of the 32nd Annual Hawaii International Conference on, IEEE.

Tudor, G. G. (2012). The Norway-Sweden certificate market in renewable electricity: A model for the European Union, University of Texas School of Law.

UNFCCC (2016). Paris Agreement, United Nations Framework Convention on Climate Change.

van Stralen, J. N. P., et al. (2013). "The role of biomass in heat, electricity, and transport markets in the EU27 under different scenarios." Biofuels, Bioproducts and Biorefining **7**(2): 147-163.

Wooldridge, M. (2009). Multi Agent Systems. Glasgow, John Wiley & Sons.

Yeh, S., et al. (2012). "National Low Carbon Fuel Standard: Policy Design Recommendations." Available at SSRN 2105897.

Yeh, S. and J. Witcover (2013). Status Review of California's Low Carbon Fuel Standard, January 2014. Institute of Transportation Studies, University of California, Davis Research Report UCD-ITS-RR-14-01.

Yeh, S. and J. Witcover (2014). Status Review of California's Low Carbon Fuel Standard-- January 2014 Issue: University of California, Davis.