



# The Effect of Electric Vehicle Deployment on Renewable Electricity Generation in an Isolated Grid System: The Case Study of Cyprus

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Decarbonisation of national economies to mitigate climate change requires transformation of the entire energy system. Investments in renewable energy technologies in the electricity supply system are increasing, but substantial effort is called for in other sectors, such as transport. While European Union member states have submitted their integrated National Energy and Climate Plans, this paper focuses on partial electrification of the transport sector as a measure to reduce carbon dioxide emissions in the isolated grid system of Cyprus in a cost-effective manner. The present work assesses the impact of electric vehicle deployment on the share of renewable electricity generation, electricity costs and carbon dioxide emissions. Quantification of these aspects is provided with an outlook until 2035. A cost-optimisation model (OSeMOSYS) is used that takes into account the electricity supply, road transport, and heating and cooling sectors. Smart charging option is also evaluated as a possibility.

**Keywords:** energy transition, electric vehicles, OSeMOSYS, renewable energy, national energy and climate plans

## INTRODUCTION

The Paris Agreement reached at COP21 highlights the commitment of 192 nations to keep global temperature rise in the 21st century well below 2°C above pre-industrial levels and to pursue efforts to limit it to 1.5°C (UNFCCC, 2015). To achieve the latter, a 45% CO<sub>2</sub> emission decrease from 2010 levels is required by 2030 (IPCC, 2018). In line with the Paris Agreement climate targets, ambitious greenhouse gas emission targets have been set by the European Union (EU) on a regional level; the EU's European Green Deal increases the 2030 reduction target for greenhouse gas emissions from 40% to at least 50% and toward 55% as compared to 1990 levels, while it aims to achieve net-zero emissions by 2050 (European Commission, 2019). According to Directive (EU) 2018/2001, a 2030 renewable energy target of 14% in the final energy consumption of the transport sector has also been set by the EU, which is applicable for each individual member state (European Union, 2018). Achievement of these targets calls for a complete transition of the energy system.

The Eastern Mediterranean is considered a 'climate hot-spot,' where temperature increases and precipitation patterns are poised to change more dramatically than the global average (Zittis et al., 2016). The region is home to 500 million people residing in usually politically volatile regions, while

the projected regional impacts make it one of the most sensitive areas of the planet (Lelieveld et al., 2016). This is the motivation behind a recent initiative launched by the Republic of Cyprus called the Cyprus Climate Initiative (CCI), which aims to identify gaps in climate-related policies of the wider region, and offer specific mitigation and adaptation measures aiming at maximum impact at the lowest possible economic, social and environmental cost (The Republic of Cyprus, 2019). Future decarbonisation efforts will be crucial in mitigating the projected impacts of climate change across the region.

Some sectors of the energy system, such as centralized electricity supply, may be easier to decarbonise than others. This culminates from the rapid technology learning rates experienced by certain renewable energy technologies in recent years (IRENA, 2018). However, the transport sector is far more challenging, as projections show that fuel diversification in this sector is expected to rise from currently low to moderate levels by mid-century (Riahi et al., 2012). The climate neutrality target of the European Green Deal identifies “Sustainable and smart mobility” as a key action. This entails a 90% reduction in greenhouse gas emissions in the transport sector by 2050, which can be achieved through a modal shift away from road transport to rail and inland navigation, automation of multimodal mobility, a reform in the pricing and taxation of fossil fuels, more stringent air pollutant emission standards for internal combustion-engine vehicles, promotion of alternative fuels and electrification of transport (European Commission, 2019).

Electrification of the transport sector is seen as a key pathway toward decarbonisation (Siskos et al., 2018; Ruhnau et al., 2019). Other direct or indirect benefits of electrification include promotion of indigenous renewable energy sources, improved energy security if electrification leads to a reduction in imported fuels, improved energy efficiency, reduced air pollutant emissions, as well as potential development of new employment opportunities (Shakya and Shrestha, 2011). However, deployment of plug-in hybrid and battery electric vehicles is currently limited to a handful of early adopters, as the high upfront cost, lack of charging infrastructure, limited range and long charging times remain important obstacles. Research and development efforts have managed to decrease the cost of battery electric vehicles considerably (Nykqvist and Nilsson, 2015; IEA, 2017; Bloomberg New Energy Finance, 2018); their cost is mainly driven by battery pack costs, while upcoming EVs are equipped with much bigger batteries (60–100 kWh) that provide similar range as conventional vehicles (i.e., up to 608 km on a single charge) (evrater, 2019). Additionally, progress in and increased availability of fast charging points aims to alleviate the issue of long charging times (Anjos et al., 2020).

An increased electricity demand in the transport sector leads to equivalent increased generation requirements on the supply side. Since investments in generation infrastructure typically have a lifetime of at least 20 years, decision makers need to consider this additional demand in their long-term planning. The impacts of electrified transport on the energy system have been examined in the available literature. Ruhnau et al. (2019) conducted a review of numerous decarbonisation scenarios for Germany up to 2050, where electrification of the transport sector is a key theme.

Keller et al. (2019) assessed scenarios of full electrification of the road transport fleet and up to 93% renewable energy share in electricity supply by 2050 for the province of British Columbia in Canada. They found that full electrification of British Columbia's road transport fleet would necessitate an increase in generation capacity of 60%, but since most of this would be based on low-cost wind and solar PV, the average cost of electricity would only rise by 9%. Siskos et al. (2018) discuss the implications of delayed action in the decarbonisation of the transport sector in the European Union and recognize the importance of electrified transport. Furthermore, the benefits offered to the grid by smart charging have been assessed and highlighted for the cases of California, where greenhouse gas and air pollutant emissions were reduced (Cheng et al., 2018), and Shanghai, where the integration of variable renewable technologies was facilitated (Jian et al., 2018). Further, smart charging has the potential to provide grid ancillary services, assisting in frequency control (Falahati et al., 2016). However, the literature mainly focuses on large interconnected systems and not on small isolated systems, for which integration of high shares of intermittent renewable energy is a concern.

The aim of the present study is to assess the impact of electrification of the transport sector on the electricity supply system of an isolated grid system and on the combined total emissions from the entire energy system. The case study of Cyprus, an EU member state, is selected as its fossil fuel-dependence, electrical grid isolation and renewable resource availability pose challenges and opportunities that can offer transferable insights to other areas, despite the system's relatively small size. Specifically, this study assesses the effect of battery electric and plug-in hybrid vehicles on the cost-optimum energy and technology mix of the electricity supply system. A range of scenarios are evaluated to identify potential synergies and obstacles presented by an increasingly electrified transport sector.

Section 2 of the paper provides important background information of the case study location, while discussing the challenges faced on the path toward an energy transition in Cyprus. Section 3 presents the model used to conduct the analysis, along with key input data and assumptions; the set of scenarios developed are also described here. The scenario results are compared and discussed in section 4. The paper concludes with a discussion on the policy implications of the analysis in section 5.

## CHARACTERISTICS OF THE CYPRIOT ENERGY SYSTEM

Energy supply in Cyprus relies mainly on refined oil products, such as diesel, gasoline, heavy fuel oil, heating oil and LPG; 91% of the total primary energy supply was covered by oil and petroleum products in 2017 (Eurostat, 2019). Due to the fact that these fuels are all imported, energy security is also a concern for energy planners. Electricity generation is fuelled primarily by heavy fuel oil and to a lesser degree diesel (EAC, 2018), the transport sector is entirely dependent on oil products, while heating is also largely reliant on fossil fuels. In terms of final energy demand, the

overall renewable energy share in the total final energy demand reached 9.7% in 2017. This is enabled by a substantial share of renewable energy in heating and cooling, due to a near universal adoption of solar water heaters in the residential sector, as well as the continuous increase of Renewable Energy Systems that are installed in the electricity supply (Republic of Cyprus, 2020).

The electricity supply system of Cyprus is based on three large thermal facilities, which have satisfied the rising electricity demand over the past few decades, but are largely carbon-intensive, inefficient and inflexible. The more modern and energy-efficient Combined Cycle Gas Turbine (CCGT) units of total capacity 440 MW installed in the Vasilikos power plant are currently fired by expensive diesel, until natural gas becomes available for electricity generation. Substitution of oil-fired generation with less carbon-intensive gas-fired generation can assist in the achievement of carbon dioxide mitigation targets, as well as in the reduction of other atmospheric pollutants (e.g., SO<sub>x</sub> and PM). Despite considerable delays in the introduction of natural gas, most recent estimates by the relevant authorities foresee that the natural gas supply infrastructure will be operational by the end of 2021.

The share of renewable energy in the 2018 electricity generation mix reached 9%. This gradually increased from 4% in 2012 and 8.6% in 2016. At the end of 2018, installed wind capacity reached 157 MW and generated 221 GWh during that year, solar PV capacity reached 123 MW and generated 195 GWh, while biogas-fired installations reached a capacity of 10 MW and contributed to the generation mix by 36 GWh (TSO Cyprus, 2019a).

Seasonal and intra-day variability in both final electricity demand and renewable energy generation add complexity in the management of electricity supply. The climate in Cyprus is typically characterized by mild winters and hot dry summers, which leads to a great variability in demand throughout the year. As demand continues to grow annually, recent statistics from 2017 show that the peak level of generation has reached 1,027 MW, while the minimum for the same year was recorded at 293 MW (Tso Cyprus, 2019b). The peak demand period is typically experienced during mid-day and afternoon hours of summer and is attributed to demand for cooling. On the contrary, low demand periods are observed in the early morning hours of spring and autumn, when demand for heating and cooling is minimal.

An important obstacle in the introduction of higher shares of renewable energy is the isolation of the Cypriot electricity supply system, as there is no grid interconnection with a neighboring country. This isolation may end if the proposed EuroAsia Interconnector materializes, linking Cyprus with Israel and Greece. If the first phase of the project proceeds as scheduled, Cyprus will be connected by a 1,000 MW HVDC line with both of these neighboring countries by the end of 2023 (Republic of Cyprus, 2020). However, considering the delays faced both in the past and recently (Financial Mirror, 2019), as well as the high capital investment of 3.5 billion EUR needed, the development of the project cannot be considered as certain.

Additionally, no electrical storage technologies have been deployed yet in the system. Incorporation of such options can provide additional flexibility to the system, as the energy arbitrage

allows for further integration of renewable energy. The National Energy and Climate Plan of Cyprus makes mention of pumped-hydro storage and lithium ion batteries as potential options, as well as thermal energy storage in the case of concentrated solar power (Republic of Cyprus, 2020).

In the first half of 2019, about 150 pure electric vehicles were registered in Cyprus, while the total number of registered passenger cars exceeded 500,000; these are further broken down to approximately 440,000 gasoline-fired, 80,000 diesel-fired and 5000 hybrid vehicles. The entire fleet size is approximately 700,000 vehicles, of which about 3,000 are diesel-powered busses, while the rest are primarily diesel-fired heavy trucks and light commercial vehicles. No other form of public transport is available. As a result, with an estimated modal share exceeding 90% of total trips, the use of privately owned vehicles is the dominant choice for passenger transport (Republic of Cyprus, 2020). It is hypothesized that despite the increased electricity demand arising from further electric vehicle deployment, electrification of the transport sector will have an enabling effect on renewable electricity generation. In fact, authorities are considering the formulation of a scheme that would support the simultaneous installation of a rooftop solar PV system and purchase of an electric vehicle. However, careful planning is needed to avoid the creation of an additional evening peak due to electric vehicle charging, which would exert additional pressure to the local grid system.

Numerous studies have been conducted to support energy planning in Cyprus. An optimisation model making use of the WASP software was originally used to guide national planning that would assist local authorities in achieving the EU's 2020 renewable energy targets (Poullikkas et al., 2011). With the collaboration of the International Renewable Energy Agency, a study then used the cost-optimisation model MESSAGE to assess the renewable energy technology potential in the electricity supply system of Cyprus in a set of six scenarios (IRENA, 2015; Taliotis et al., 2017c). Building on this, a more detailed model was developed within the OSeMOSYS modeling framework, including code enhancements that considered short-term system constraints, in order to assess a range of scenarios for natural gas introduction in the energy mix of Cyprus (Taliotis et al., 2017b); this OSeMOSYS model has since been expanded to include the transport and heating and cooling sectors. To examine the functionality of the OSeMOSYS model and assess the impact of renewable energy integration on grid stability, a capacity expansion outlook was tested with a power systems model developed in PLEXOS (JRC, 2016). Despite the aforementioned studies focusing on the electricity supply and primary energy supply sectors, no analysis is available in the literature focusing on the transport sector of Cyprus. No study exists that assesses the impact of transport electrification on the island's energy mix.

## MATERIALS AND METHODS

### Modeling Approach

The existing model of the Cypriot energy system, developed in OSeMOSYS (Taliotis et al., 2017b), is used as basis for the analysis

and is updated to support the formulation of the National Energy and Climate Plan of the Republic of Cyprus (2020). OSeMOSYS is a demand-driven cost-optimisation model, the objective function of which is to satisfy an exogenously defined final energy demand at the least possible cost (Howells et al., 2011). Taking into account a range of assumptions with regards to techno-economic characteristics of technologies, fuel prices, emission limits and other system constraints, the model identifies a cost-optimal technology and energy mix. OSeMOSYS has been used in several applications of national, regional and global focus (Löffler et al., 2017; Pinto, de Moura et al., 2017; Gardumi et al., 2018; Niet et al., 2018; Rady et al., 2018; Sridharan et al., 2019), while its maturity and technical capability for serious use to support energy planning have been recognized in a study comparing 31 open source energy system tools (Groissböck, 2019).

The OSeMOSYS model of Cyprus has three modules representing the three key energy sectors: electricity supply, road transport, heating and cooling. It makes use of OSeMOSYS code enhancements that consider grid flexibility constraints, such as operating reserves demand and ramping rates of thermal units. OSeMOSYS model results from this enhanced code have been validated against a linked framework of a separate cost-optimisation model (TIMES) and a power systems model (PLEXOS), illustrating comparable results for the case of Ireland (Welsch et al., 2014). This is especially important in the case of Cyprus, since due to its electrical grid isolation there are concerns regarding grid stability in case of a high penetration of variable renewable energy technologies in the system. A detailed power system analysis with the effects at each bus is not carried out and the aspect of grid stability is considered out of the scope of this work. Assessment of this aspect would require a detailed power flow analysis for each load and generation bus, which would require employment of power systems models with high temporal and technical detail and offer different insights than the present analysis.

It should be highlighted that the present modeling effort aims at understanding the plausible future energy and technology choices to be followed by end-users, within the framework of existing and planned policies and measures. In this sense, since fuel taxation is an integral part of national energy policy, fuel taxes are replicated within the model, so as to represent system conditions from the consumer's perspective. Furthermore, the objective is not the identification of a cost-optimal solution for a suite of renewable energy and emission targets. As such, no hard constraints in regards to specific targets are included in the model, unless backed-up by specific policies. Therefore, the only target related constraint implemented in the model is associated with the necessity to cut down SO<sub>x</sub> emissions in 2020.

In order to allow an analysis of the impacts of electrification of the transport sector, a set of scenarios is developed, for which identified indicators for the comparison include the level of renewable energy technology investments and generation, estimates of curtailment of renewable electricity generation, the evolution of average electricity cost and projections of greenhouse gas emissions. The following three scenarios are examined:

## Reference (REF)

This scenario assumes that the current trends in terms of vehicle fleet continue in the transport sector. Blending of conventional fuels with imported biofuels is allowed, but only minimal investments in alternative vehicle technologies occur. The penetration of electric vehicles is limited to existing levels in this scenario. Measures in the rest of the energy system are derived from the 'With Existing Measures' (WEM) scenario of the National Energy and Climate Plan of Cyprus (Republic of Cyprus, 2020). Hence, constraints have been implemented to have representation of the evolution of the energy system largely in line with the official plans of the government<sup>1</sup>.

## Electrified TRANSPORT (ET)

Additional to the measures foreseen in the REF, in this scenario plug-in hybrid (PHEV) and battery electric (BEV) vehicles are allowed to be deployed, if deemed part of the cost-optimal solution. A predefined charging profile is assumed in this scenario. It should be clarified that no forced investments in PHEV and BEV are considered in this scenario, while no financial incentives are provided to consumers to promote the purchase of these vehicles.

## Smart Charging (SC)

Building on the ET, this scenario examines the extent to which smart charging will enable further electrification of the transport sector and an equivalent increase in renewable electricity generation. In essence, the period under which charging of electric vehicles occurs is decided through the optimisation of the model. No financial incentives are provided in this scenario either.

None of the above scenarios consider development of the interconnector with Greece and Israel, due to the high cost and delays faced by the project, as well as the fact that the present paper aims to analyze the impacts of electrified transport in an isolated system.

## Overarching Assumptions

The scenarios adopt low fuel price assumptions so as to be in line with the National Energy and Climate Plan of Cyprus (Table 1; Republic of Cyprus, 2020). As such, the low oil price scenario from an earlier IEA report is used as a basis (IEA, 2015). Since the electricity generation in the European Union falls under the Emission Trading Scheme (ETS), the latest ETS carbon price forecast is also used (European Commission, 2016). The techno-economic characteristics of renewable energy technology options for the generation sector (Table 2) are taken from an earlier study conducted for the Ministry of Energy of Cyprus (Taliotis et al., 2017a).

Storage technology options are considered in the study as a way to allow higher deployment of intermittent renewable energy in the system. Namely, the possibility for the development of one 130 MW (1040 MWh) pumped hydro facility is included, while lithium ion batteries developed either for centralized storage

<sup>1</sup> A noticeable example is the planned addition of a solar thermal facility of 50 MW in the electricity supply sector in 2022.

**TABLE 1** | International Fuel prices assumed in the model.

		2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2035
Oil	EUR2016/GJ	5.12	5.40	5.69	5.99	6.30	6.64	6.71	6.79	6.86	6.93	7.00	8.51
Gas	EUR2016/GJ	5.16	5.43	5.73	6.03	6.34	6.68	6.76	6.84	6.91	6.98	7.06	8.57
Carbon price ETS sectors	EUR2016/ton CO <sub>2</sub>	15.5	17.6	18.6	20.7	21.7	23.3	25.9	27.9	30.0	32.1	34.7	43.5

The analysis adopts low fossil fuel price projections, in line with the National Energy and Climate Plan of Cyprus (Republic of Cyprus, 2020). On the other hand, following recommendations of the European Commission to EU member states, the latest ETS carbon price forecast is also used (European Commission, 2016).

**TABLE 2** | Techno-economic assumptions of renewable energy technologies for generation.

	Investment cost (EUR2016/kW)			Fixed cost O&M cost (EUR2016/kW)	Capacity factor	Lifetime (years)
	2020	2030	2035			
Utility-scale PV	1,161	886	749	9	18.5%	20
Wind	1,394	1,330	1,298	53	16%	25
Biomass-biogas	2,461	2,438	2,426	62	48.5%	30
Rooftop PV	1,467	1,241	1,129	12	18.5%	20
CSP with 6 h storage	4,410	3,724	3,577	58.2	50.8%	25

The cost assumptions are derived from literature but provide a good representation of costs in the context of Cyprus.

or behind-the-meter storage are considered, as in the Cypriot NECP (Republic of Cyprus, 2020). Even though Bloomberg NEF projects battery pack costs for stationary applications at 62 EUR2016/kWh by 2030 (Bloomberg New Energy Finance, 2018), more moderate price forecasts from IRENA's storage cost-of-service tool are used in this study (IRENA, 2017). Nonetheless, these assume a significant cost improvement from 286 EUR2016/kWh in 2020 to 148 EUR2016/kWh by 2030. For the period after 2030, it is assumed that cost improvements would slow down, reaching an installation cost of 134 EUR2016/MWh by 2035. IRENA's publication also projects that by 2030, the round-trip efficiency of Li-ion batteries would improve to 95%, while the lifetime of the technology would be extended to 15 years.

In regards to the transport sector, different modes of transport, fuel and technology options are considered. It has to be clarified that the assumed purchase cost of the various vehicle technologies is kept identical across all scenario runs, as the present effort focuses on some of the external factors that affect the deployment of these technology options. Information regarding techno-economic assumptions and transport demand projections by mode, which are aligned to the assumptions of the official NECP (Republic of Cyprus, 2020), is provided in the Appendix.

## Charging Profile

The degree at which electric vehicles exert pressure on the electricity supply system is largely affected by the assumed period of vehicle charging. This is a very important aspect, as an increased deployment of electric vehicles has the potential to drastically alter the overall demand profile of the respective electricity system. Numerous studies in the literature highlight the importance of identifying a representative charging profile for electric vehicles (Robinson et al., 2013; Speidel and Bräunl, 2014; Brady and O'Mahony, 2016; Xydias et al., 2016; Wang et al., 2017). Since very little information exists in Cyprus due

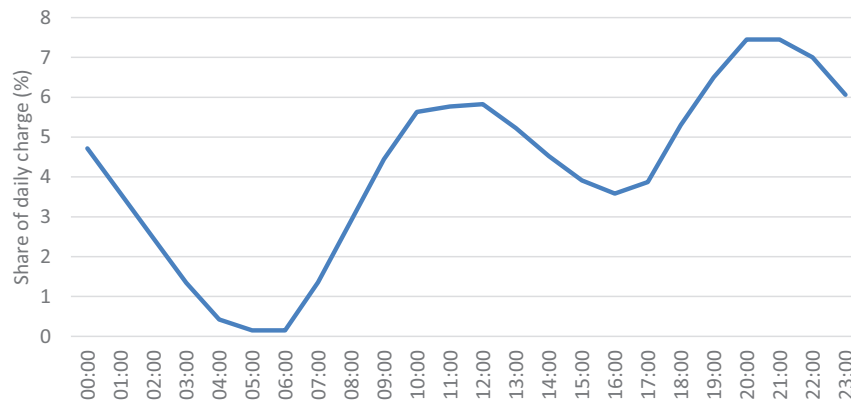
to the currently limited BEV deployment, the adopted charging profile is retrieved from a British case study in available relevant literature (Robinson et al., 2013). As shown in **Figure 1**, the daily charging profile of private vehicles used in the ET scenario is characterized by two peaks; one in the period 10:00–12:00 and one during 20:00–21:00, with the latter being the highest. This profile is assumed to be representative of Cypriot reality, as the first peak is driven by charging after arriving at the owners' workplace and before lunch-break, while the evening peak is driven by charging at home.

## RESULTS AND DISCUSSION

### Technology Investments and Generation Mix

The scenario results indicate that penetration of renewable energy technologies rises with increased electrification in the transport sector. Specifically, the extent of photovoltaic deployment is higher by 141 MW and 255 MW in the ET scenario as opposed to the REF scenario in 2030 and 2035, respectively (**Table 3**). The difference is greater in the SC scenario; solar PV capacity is higher by 215 MW in 2030 and 380 MW in 2035 than in the REF case. Despite the higher renewable energy penetration in both instances, the investment outlook for the other generation technologies remains relatively unchanged with one exception: new installations in CCGT are higher by 216 MW in the ET scenario in 2035. This can be explained by the need for additional electricity generation when electric vehicles are deployed in the ET scenario; this demand is satisfied with additional solar PV capacity in the SC scenario, enabled by smart charging.

Deployment of storage technologies varies considerably between scenarios. When the fleet of electric vehicles is limited at current levels in the REF scenario, 170 MW (680 MWh) of lithium ion batteries are deployed by 2030. In the ET scenario,



**FIGURE 1 |** Daily charging profile of private BEVs and PHEVs (adapted from Robinson et al., 2013). Due to insufficient information on charging behavior of electric vehicle owners in Cyprus, information from relevant literature is used as input to the model. Two peaks are observed in the assumed profile, one in the middle of the day, which corresponds to the peak PV generation period, and a larger peak in the evening.

**TABLE 3 |** Capacity evolution (in MW) for each technology in each scenario (MW).

	2020			2025			2030			2035		
	All	REF	ET	SC	REF	ET	SC	REF	ET	SC		
Existing thermal	1,478	1,120	1,120	1,120	1,120	1,120	1,120	608	608	608		
New CCGT	–	432	432	432	432	432	432	432	648	432		
New ICE	–	–	–	–	–	–	–	–	–	–		
New ST	–	–	–	–	–	–	–	–	–	–		
New GT	–	62	62	62	62	62	62	62	62	62		
Light fuel oil CHP	–	–	–	–	–	–	–	15	–	9		
Solar PV	312	639	751	665	1,013	1,157	1,227	1,624	1,879	2,013		
Solar thermal	–	50	50	50	50	50	50	50	50	50		
Wind	174	174	174	174	174	174	174	174	174	174		
Biogas	17	50	50	50	50	50	50	52	50	50		
Pumped hydro	–	–	–	–	–	130	–	130	130	130		
Li-ion batteries	–	34	11	28	170	11	127	408	141	330		
Total generation capacity	1,981	2,526	2,638	2,553	2,900	3,044	3,115	3,017	3,471	3,398		

The total generation capacity indicated excludes capacity of storage technologies (i.e., pumped hydro and lithium ion batteries). The results indicate substantial investments in new CCGT and solar PV until 2035 in all scenarios. Additionally, investments in storage technologies are foreseen, which vary considerably across scenarios. Some of the results refer to planned additions (e.g., additions in wind of 17 MW in 2020 and solar thermal of 50 MW in 2022) or are capped (e.g., pumped hydro is limited to a maximum of 130 MW) due to boundaries associated with official plans of the government.

capacity of batteries is reduced to 11 MW (45 MWh), but pumped-hydro storage is developed, giving an overall storage capacity of 1,085 MWh. This additional storage capacity is used for energy arbitrage of the additional renewable electricity generation, which is partially used to satisfy the evening peak charging period. Storage capacity differences are noticed also between the ET and SC scenarios (Table 4). It should be noted that the capacity of the pumped-hydro facility is limited to exactly 130 MW (1,040 MWh) and the model does not have the option to install a different capacity, be it lower or higher. As such, in cases with low storage needs, the cost-effectiveness of batteries as an option is higher.

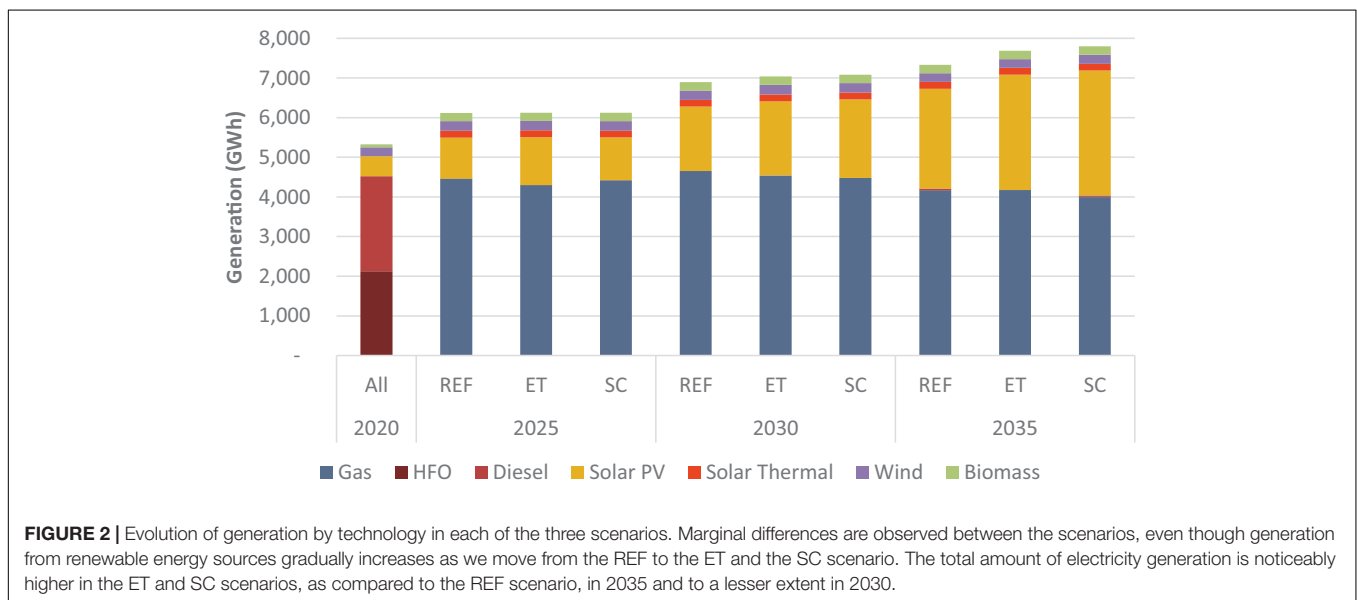
In terms of electricity generation, the absolute contribution of fossil-fired generation in the REF scenario of the present analysis remains relatively stable between 4,200 and 4,600 GWh (Figure 2). Gas-fired generation is the dominant source of

electricity in all scenarios, while even after the introduction of natural gas in the system small amounts of diesel-fired generation can be observed in certain years; the latter is used to satisfy peak demand periods. Nonetheless, the rising electricity demand is met primarily with new solar PV installations. This finding is consistent with EU's Reference Scenario 2016 for Cyprus; this also indicates that thermal generation will marginally be affected by increasing solar PV generation, which in turn satisfies the increase in electricity demand (European Commission, 2016).

The degree of electrification of the transport sector achieved in scenarios ET and SC leads to an increase in the overall electricity demand; electricity generation increases as a result. The ET and SC scenarios are quite comparable, with the exception that renewable electricity generation is higher for the majority of the modeling horizon in the latter. For instance, renewable electricity generation is higher by 100 GWh in 2030 and 245 GWh in 2035

**TABLE 4 |** Summarized comparison of scenario results.

	2020		2030		2035		
	All	REF	ET	SC	REF	ET	SC
Registered electric vehicles	100	100	30,989	46,847	–	103,657	119,514
Electricity consumption in transport sector (GWh)	0.3	0.3	114	175	–	360	419
RES-electricity share	15.0%	32.5%	35.5%	36.7%	42.5%	45.7%	48.2%
RES-transport share	2.2%	1.8%	4.3%	5.7%	1.7%	12.7%	15.1%
Storage (MWh)	–	680	1,085	509	2,671	1,603	2,360
Curtailment of solar PV	0.1%	1.1%	0.1%	0.5%	4.5%	4.4%	3.5%
Curtailment of wind	8.9%	3.6%	1.3%	3.1%	9.3%	9.2%	6.9%
Import dependence (share of TPES)	90.8%	83.5%	82.3%	81.8%	78.9%	76.8%	75.8%



in the SC scenario; this corresponds to an increase of 4% and 7%, respectively, from the ET scenario. The difference can be attributed to the larger electric vehicle fleet and the flexibility offered by smart charging.

Similarly, as compared to the REF scenario, renewable energy generation as a whole is higher in the ET case by 255 GWh and 400 GWh in 2030 and 2035, respectively. Renewable electricity generation reaches 35.5% and 45.7% in the ET scenario and 32.5% and 42.5% in the REF scenario, in 2030 and 2035, respectively. It should be mentioned that the increased renewable energy leads to a marginal reduction in fossil-fired generation. This reduces by 110 GWh in 2030 and 45 GWh when electrification of the transport sector is enabled. The increase in renewable electricity generation can be attributed to the flexibility offered by electric vehicles, as evident in 2035 when storage capacity is lower in the ET scenario, yet the renewable energy share in electricity is higher.

The higher renewable energy share in the ET scenario is on one hand achieved due to the fact that electricity from photovoltaics can be used directly to charge the electric vehicle fleet. It should be noted that, as shown in **Figure 1**, two charging peaks exist; one at midday and one in the late evening and overnight. The

former coincides with the peak photovoltaic generation period. The latter, which is also the highest charging peak occurs during periods of zero generation from photovoltaics, but at a time where electric vehicle charging can help to keep thermal plants online for longer periods. It should be mentioned that additional to the renewable energy investments, thermal plants with higher ramping capability are also deployed on the supply side; 62 MW of flexible ICE units become developed for the period 2020–2040. Similarly, two new CCGT units of 216 MW each are developed in all scenarios by 2030, while a third CCGT unit is needed by 2035 in the ET scenario.

Most electric vehicle purchases occur after 2025 in both the ET and SC scenarios, hence differences in the results are primarily observed in the period 2030–2035. A detailed breakdown of the vehicle fleet projection in each scenario for all modes of transport and vehicle technologies is provided in the Appendix. **Table 4** provides an overview of key results from the three scenarios. Penetration of electric vehicles is highest in the SC scenario; for instance, in 2030 the electric vehicle fleet is 50% higher in SC than in the ET scenario. Smart charging in the former case allows vehicles to be charged when cheap electricity is available, whereas peak charging in the latter scenario coincides with

peak electricity demand and low renewable energy generation periods. Thus, electric vehicle deployment is more cost-effective in the SC scenario.

The increased electric vehicle deployment results in an equivalent increase in electricity demand. Consumption of electricity in the transport sector corresponds to 2% and 3% in 2030, and 5% and 6% in 2035 of the total final electricity demand in the ET and SC scenarios, respectively. However, this small increase in electricity demand increase allows the electrification of up to 6% and 13% of the total road transport vehicle fleet in 2030 and 2035, respectively in the SC scenario.

Moreover, the renewable energy share in electricity is highest in the SC case, while it is lowest in the REF case throughout the model horizon. This has an analogous effect on the renewable energy share of the transport sector. Even though storage capacity is higher in the ET case than the SC case in 2030, the situation reverses in 2035. The scenario with the highest storage capacity in each of these instances coincides with the lowest level of renewable energy curtailment. As a result of the increasing renewable energy share, when moving from the REF to the ET and the SC scenarios, the import dependence decreases (Table 4); this indicator quantifies the amount of imported energy as a share of Total Primary Energy Supply (TPES). This illustrates the benefits offered by increased electrification to energy security, as it reduces reliance on imported fossil fuels.

Focusing at the end of the model horizon, it is interesting to note that storage capacity is higher in the REF scenario than the ET and SC scenarios in 2035, despite the lower renewable energy share. The necessity for more electrical storage in the REF scenario can be attributed to the lack of adequate electricity demand that can absorb electricity generation from intermittent renewable energy technologies.

Overall, the technology deployment results indicate that electric vehicles have an enabling effect on renewable energy technology deployment. They also affect the requirements for storage, while assist in limiting renewable energy curtailment to lower levels. This effect is enhanced when smart charging is implemented.

## Impact on Greenhouse Gas Emissions and System Costs

An important finding of the analysis relates to the fact that fossil-fired generation and, hence, greenhouse gas emissions in the electricity supply sector decrease with increased penetration of renewables in the ET and SC scenarios. At the same time, deployment of electric vehicles as alternatives to internal combustion engine vehicles leads to a simultaneous reduction in greenhouse gas emissions in the transport sector. As such, an overall greenhouse gas emissions decrease can be observed. The combined impact on these emissions in the electricity supply sector, which falls under the EU's Emission Trading Scheme (ETS), and the non-ETS sectors, which includes the transport sector, is shown in Table 5. In comparison to the REF scenario, by 2030, a reduction of 2.7% and 3.7% in overall energy system emissions is achieved in the ET and SC scenarios, respectively;

**TABLE 5** | Energy related greenhouse gas emissions in the ETS and non-ETS sectors in each scenario (kt CO<sub>2</sub> eq).

	2020		2030			2035	
	All	REF	ET	SC	REF	ET	SC
ETS sector	3,683	2,334	2,274	2,266	2,125	2,074	2,050
Non-ETS sectors	2,989	2,940	2,857	2,813	2,924	2,643	2,618
<i>of which in transport</i>	<i>2,046</i>	<i>2,106</i>	<i>2,024</i>	<i>1,980</i>	<i>2,126</i>	<i>1,874</i>	<i>1,833</i>
Total	6,673	5,274	5,131	5,079	5,049	4,717	4,668

*The portion of the non-ETS sector which corresponds to the transport sector is shown separately, to allow a direct comparison of the impact of each scenario on the transport sector separately and the energy system in its entirety.*

**TABLE 6** | Average GHG intensity (g CO<sub>2</sub> eq/km) in the road transport sector in each scenario.

	2020		2030			2035	
	All	REF	ET	SC	REF	ET	SC
GHG intensity in road transport	291	262	255	251	246	224	220

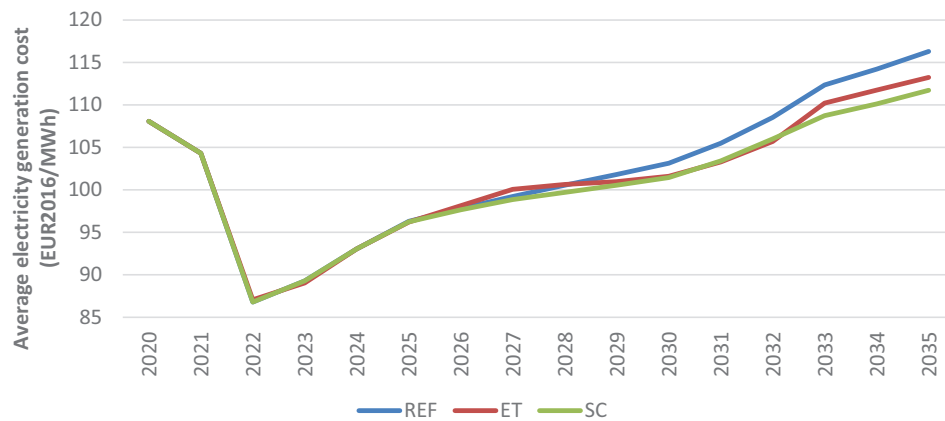
*The GHG intensity is calculated by accounting for all emissions connected to fuel consumption in the transport sector and dividing it by the total distance covered by all vehicle categories. Fuel consumption includes electricity consumption, using an average carbon intensity of electricity supply in each specific year for each scenario separately. It is evident that electrification of transport facilitates partial decarbonisation of the transport sector, while smart charging can amplify this effect, albeit marginally in the present analysis.*

the overall reduction increases to 6.6% and 7.5% in each of the two scenarios by 2035.

In order to estimate the overall greenhouse gas intensity of the road transport fleet, the lifecycle carbon intensity factor for each fuel is taken from Directive (EU) 2015/652 (European Union, 2015), while the carbon intensity of electricity is estimated directly from the model results. The total carbon emission of the road transport fleet is then divided by the total distance traveled by the fleet, so as to assess the evolution of the fleet's carbon intensity across the scenarios (Table 6); this includes all vehicle categories, such as passenger cars, light commercial vehicles and heavy-duty vehicles. An improvement is noticed in all scenarios for the period 2020–2035, but this is greater in the scenarios with electrified transport. In the REF scenario, a reduction of 15% is achieved during this period by 2035; the corresponding reductions amount to 23% in the ET and 24% in the SC scenario.

The aforementioned differences in generation mix, technology investments and emissions affect the average electricity cost of the system. In the REF scenario, electricity cost varies between 108 EUR<sub>2016</sub>/MWh in 2020 to 102 EUR<sub>2016</sub>/MWh in 2030 and 116 EUR<sub>2016</sub>/MWh in 2035 (Figure 3). When electric vehicles are deployed, electricity cost decreases in the ET scenario to 102 EUR<sub>2016</sub>/MWh in 2030 and 113 EUR<sub>2016</sub>/MWh in 2035. Furthermore, in the SC scenario, where smart charging is enabled, electricity cost is comparable to the ET case, but decreases slightly to 112 EUR<sub>2016</sub>/MWh





**FIGURE 3 |** Average electricity generation cost projection in the three scenarios. The electricity cost is the same across scenarios until 2025, as noticeable differences in the electrification of transport only occur after this point. Even though differences between the scenarios are marginal, the REF scenario illustrates the highest electricity cost, while the lowest is observed in the SC scenario.

in 2035. Despite the additional level of investments in solar PV and an increased electricity demand in the ET and SC scenarios, deployment of inexpensive generation options in combination with electrification of transport results in small, albeit noticeable considering the size of Cyprus, cost savings. By 2035 the annual cost savings in electricity supply correspond to 22 million EUR2016 and 34 million EUR2016 in the ET and SC scenarios, respectively.

## CONCLUSION

The analysis presented in this paper provides a strong indication that electrification of the transport sector can assist in the integration of a higher share of renewable energy technologies in the Cyprus electricity supply. This also leads to a reduction of carbon dioxide emissions, without compromising electricity prices.

The number of charging points will have to increase considerably to allow the envisioned electric vehicle deployment, while operation within a broader smart grid will have to be developed for the implementation of smart charging. Nonetheless, additional to the technical infrastructure required to enable such an operation, institutional infrastructure needs to be established to allow consumers to actively participate in the future electricity market. The adoption of time-of-use electricity tariffs is a measure that will promote vehicle charging in low electricity demand or peak renewable energy generation periods. Incentives to consumers will encourage vehicle owners to follow a flexible charging schedule based on the availability of cheap electricity and intra-day fluctuations of electricity demand.

The present study has certain limitations. Cost-optimisation models assuming perfect competition, perfect foresight and a rational economic behavior by consumers are not fully representative of the decision criteria influencing investments, especially so in the transport sector. Similarly, the model assumes perfect access to information and a simultaneous reaction of

consumers to real-time energy prices, which does not reflect reality. However, the analysis strives to illustrate the exploitable potential of the respective technology and energy mix in each of the scenarios.

The analysis illustrates that the charging profile of electric vehicles can have a direct impact on the generation mix of the Cyprus system. As the battery pack characteristics of electric vehicles may change in the future to accommodate longer ranges, charging may require higher energy densities, leading to more noticeable peaks, or longer charging times, thus affecting the charging behavior of vehicle owners. This is an aspect that will have to be assessed further as it can potentially introduce challenges in handling sudden electricity load variations, thus reducing the enabling effect of electric vehicles on renewable energy technologies observed in the present paper.

Future work will include development of a scenario assuming operation of a vehicle-to-grid system to assess the further impact of this aspect on renewable energy, electric vehicle deployment, as well as the effect on electric storage investment outlook. Further, adoption of demand profiles based on local data can be enabled when these become available with time.

Finally, the presented work provides insights to some of the benefits of electrified transport and provides results within certain predefined boundaries. It does not make a comparison to the cost of other measures needed to achieve deep decarbonisation of the entire energy system. As an EU member state, Cyprus must adhere with the objectives set out in the European Green Deal. As such, future enhancements of the present work will have to explore pathways for net-zero emissions by 2050, considering the broader financial implications of various decarbonisation strategies.

## DATA AVAILABILITY STATEMENT

The datasets for this article are not publicly available because of contractual confidentiality restrictions in the relevant

support provided to the authorities of Cyprus. Requests to access the datasets should be directed to CT, c.taliotis@cyi.ac.cy.

and reviewed and edited original draft. All authors contributed to the article and approved the submitted version.

## AUTHOR CONTRIBUTIONS

CT performed conceptualization, methodology, data curation, simulations, visualization, and original draft. NF performed conceptualization, supervision, and original draft. GP, FG, VS, and MK reviewed and edited the original draft. CP supervised

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**Conflict of Interest:** The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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## APPENDIX

**TABLE A1** | Existing vehicle fleet in 2017.

Vehicle category	Type	Number of vehicles
Passenger cars	Diesel	86,500
	Gasoline	432,000
	Gasoline hybrid	5,200
	BEV	100
Busses	Diesel	3,000
Motorcycles	Gasoline	48,000
Trucks	Diesel	12,400
Light commercial vehicles	Diesel	114,400

**TABLE A2** | Vehicle purchase cost (EUR2016/unit).

Category	Technology	2020	2025	2030	2035
Passenger cars	Diesel	17,063	17,063	17,063	17,063
	Gasoline	16,230	16,230	16,230	16,230
	Hybrid gasoline	19,764	19,636	19,509	19,690
	Hybrid diesel	19,654	19,459	19,265	19,058
	PHEV gasoline	26,680	26,368	26,061	25,697
	PHEV diesel	27,500	27,179	26,862	26,486
	BEV	28,553	27,968	27,395	27,087
	CNG	18,366	18,366	18,366	18,366
	LPG conversion	1,463	1,463	1,463	1,463
Motorcycles	Gasoline	5,762	5,762	5,762	5,762
Busses	Diesel	292,553	292,553	292,553	292,553
	CNG	382,824	379,011	375,235	371,208
	BEV	409,012	400,639	392,437	388,012
Trucks	Diesel	31,693	31,693	31,693	31,693
	BEV	123,906	121,369	118,885	117,544
	CNG	56,073	56,073	56,073	56,073
Light commercial vehicles	Diesel	19,791	19,791	19,791	19,791
	BEV	45,941	45,000	44,079	43,582
	PHEV	31,700	31,330	30,964	30,531
	Hybrid diesel	23,056	22,826	22,599	22,356

Note: An additional cost of 500 EUR2016 for charging infrastructure is assumed for each BEV and PHEV purchase.

**TABLE A3** | Total mileage projection for each mode of transport.

Million veh-km	2020	2025	2030	2035
Busses	68	73	78	84
Light commercial vehicles	1,917	2,057	2,197	2,366
Motorcycles	208	223	238	257
Passenger cars	6,753	7,245	7,737	8,335
Heavy duty vehicles	68	73	78	84

**TABLE A4** | Fuel efficiency projections (MJ/km).

		2020	2025	2030	2035
Busses	Diesel	11.92	11.56	11.27	10.70
	BEV	4.33	4.06	3.91	3.81
	Natural gas	10.44	10.12	9.86	9.36
Light commercial vehicles	Diesel plug-in hybrid	2.76	2.69	2.60	2.47
	BEV	1.22	1.20	1.16	1.11
	Diesel	3.19	2.94	2.75	2.61
Motorcycles	Gasoline	1.20	1.20	1.21	1.20
Passenger cars	Diesel plug-in hybrid	2.76	2.69	2.60	2.47
	BEV	0.94	0.89	0.89	0.87
	Gasoline plug-in hybrid	2.20	2.15	2.17	2.14
	Diesel	3.06	2.87	2.71	2.58
	Gasoline hybrid	2.15	2.15	2.11	2.06
	Gasoline	2.99	2.87	2.74	2.60
	LPG	2.52	2.48	2.44	2.39
Trucks	Natural gas	2.54	2.49	2.50	2.47
	BEV	3.40	3.27	3.14	3.05
	Diesel	9.37	9.30	9.05	8.53
	Natural gas	8.20	8.14	7.92	7.46

**TABLE A5** | Scenario results on vehicle fleet projections in each scenario.

		2020			2025			2030			2035		
		All	REF	ET	SC	REF	ET	SC	REF	ET	SC		
Passenger cars	Diesel	69,175	40,372	40,372	40,372	11,570	11,570	11,570	-	-	-		
	Diesel hybrid	-	-	-	-	-	-	-	-	-	-		
	Diesel PHV	-	-	-	-	-	-	-	-	-	-		
	Gasoline	471,730	539,890	539,790	539,790	580,422	550,506	535,307	574,764	473,856	458,657		
	Gasoline hybrid	5,170	5,170	5,170	5,170	32,710	32,710	32,710	98,633	98,633	98,633		
	Gasoline PHV	-	-	-	-	-	-	-	-	-	-		
	BEV	100	100	100	100	100	29,916	45,116	-	100,908	116,107		
	LPG	214	739	739	739	1,174	1,174	1,174	963	963	963		
	Natural gas	-	-	-	-	-	-	-	-	-	-		
	Hydrogen	-	-	-	-	-	-	-	-	-	-		
Busses	Diesel	3,014	3,230	3,230	3,230	3,450	3,450	3,450	3,715	3,715	3,715		
	Diesel hybrid	-	-	-	-	-	-	-	-	-	-		
	BEV	-	-	-	-	-	-	-	-	-	-		
	CNG	-	-	-	-	-	-	-	-	-	-		
MCs	Gasoline	50,925	54,667	54,667	54,667	58,383	58,383	58,383	62,806	62,806	62,806		
	BEV	-	-	-	-	-	-	-	-	-	-		
Trucks	Diesel	12,978	13,923	13,625	13,764	14,868	13,795	13,136	16,016	13,268	12,610		
	BEV	-	-	297	159	-	1,073	1,731	-	2,748	3,407		
	Natural gas	-	-	-	-	-	-	-	-	-	-		
Light trucks	Diesel	119,614	128,323	128,323	128,323	137,032	137,032	137,032	147,625	147,625	147,625		
	BEV	-	-	-	-	-	-	-	-	-	-		
	PHEV diesel	-	-	-	-	-	-	-	-	-	-		
	Hybrid diesel	-	-	-	-	-	-	-	-	-	-		
	Grand total	732,920	786,414	785,578	786,314	839,709	839,609	839,609	904,521	904,521	904,521		