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Rapid decarbonisation of Paris, Lyon and Marseille's power, transport and building sectors by coupling rooftop Solar PV and Electric Vehicles

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Abstract

Meeting the European Commission's 'Fit for 55' climate goals by the year 2030 in the context of the trilemma of security of supply, environmental sustainability, and competitiveness will require concerted efforts from the Member States on all fronts. Among others, it will require optimised techno-economic solutions that offer sustainable decarbonisation pathways for the concurrent decarbonisation of many sectors of the economy. This paper attempts to provide empirical evidence of the 'rooftop solar PV+EV concept' efficacy as a promising pathway to decarbonise France's transport, power and building sectors concurrently. Using the System Advisor Model (SAM), we find that if rooftop solar PV is installed on half of the available roof space, and if half of the passenger vehicle owners replace their internal combustion engine vehicles (ICEVs) with EVs by 2030, then France can meet 20%-42% of total electricity demand in the three most populous cities. Moreover, the solar PV+EV coupling can reduce CO₂ emissions from passenger vehicle use and electricity generation by 43%-48%. Also, the coupling can be a potentially worthwhile investment with a payback period of 2-3 years, a levelised cost of energy (LCOE) of about €0.04/kWh, and a net present value (NPV) of €6-19 billion without a feed-in tariff. We analyse the potential implementation challenges of the 'rooftop solar PV+EV concept' and propose some solutions. Finally, we argue that coupling rooftop solar PV+EV in cities is a cost-effective strategy to decarbonise urban energy, transport and building sectors concurrently. Therefore, the government should consider enacting combined rooftop solar PV+EV decarbonisation policies that offer economic and environmental benefits.

Keywords: Decarbonisation; rooftop solar PV; electric vehicle; energy transition; market design; public policy.

Highlights

- Rooftop solar PV+EV can meet 20%-42% of electricity demand in France's three most populous cities by 2030.
- Rooftop solar PV+EV can reduce CO₂ emissions from vehicle use and power generation by 43%-48% by 2030.
- Coupling PV+ EV can be a potentially worthwhile investment with a payback period of 2-3 years, an LCOE of €0.04/kWh, and an NPV of €6-19 billion without a feed-in tariff by 2030.
- Coupling rooftop solar PV+EV in cities is a cost-effective strategy to decarbonise urban energy, transport and building sectors concurrently.
- The government should consider enacting PV+EV combined decarbonisation policies that can offer economic and environmental benefits.

1. Introduction

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The EU has set ambitious targets to reduce net emissions by at least 55% by 2030 compared to 1990 (coined “Fit for 55”) and to make Europe the first climate-neutral continent by 2050. Energy use accounts for 75% of the EU’s emissions. Therefore, the transformation of the energy system is central to its climate ambitions. Moreover, the EU has identified renewable energy as a critical driver to reduce emissions. Thus, to achieve the “Fit for 55” target, the EU Renewable Energy Directive increased the overall binding target of renewable energies share in the EU’s energy mix from the current 32% to 40% (EU, 2021). As the EU implements its 55% emissions reduction target, France has also increased its 2030 targets to reduce emissions and increase the share of renewable energies (IEA, 2021a). The multiannual energy plan² (PPE) and the national low-carbon strategy³ (SNBC) set out the government’s strategic energy policy priorities. The PPE sets out two fundamental priorities: reducing energy consumption, particularly fossil fuel consumption, and developing renewable energy sources. The PPE also commits to developing clean mobility and reducing the transport sector energy consumption by 11.5%. The PPE hopes to reach a target of 32% in final energy consumption from renewables by 2030 (PPE, 2017; 2019). Likewise, the SNBC aims to cut greenhouse gas emissions by 40% by 2030 and 75% by 2050 (SNBC, 2017).

Finding economically and environmentally sustainable energy pathways that simultaneously assure the security of supply to meet the “Fit for 55” targets is a herculean task. For example, the variable nature of solar PV makes its large-scale integration challenging for the system’s stability (Thompson and Perez, 2020). In this regard, decentralised installations such as rooftop solar PV offer a promising solution. The falling price of solar PV panels in recent years has led to a growth in the uptake of self-consumption (decentralised) solutions such as rooftop solar PV. Although still modest, the installation is rapidly increasing. In France, several million households could use rooftop solar PV within 15 years (RTE, 2019b). Moreover, rooftop solar PV is the least invasive distributed energy as it does not take up valuable natural land and offers a considerable potential to supply power to consumers directly with minimal distribution loss (Kobashi et al, 2021).

The transport sector is responsible for 38% of France’s energy-related CO₂ emissions and 27% of its GHG emissions. Transport is France’s biggest emitter sector accounting for a large share of air pollutant emissions, notably nitrogen oxide (NO_x) (56%), PM_{2.5} (18%), as well as 20% of total non-methane volatile organic compounds (IEA, 2021a). Many transport activities are still fossil fuel-powered and thus drive CO₂ emissions. Shifting the sector’s power source to electricity is an apparent sustainable means to reduce its emissions (Kobashi et al., 2021). Electric vehicles (EVs) are poised to play a vital role in reducing dependency on non-renewable fuels and the transportation sector’s environmental implications (Khan et al., 2023). Sales of EVs are increasing in the EU, primarily supported by government policies. In 2021, EV sales more than doubled the sales in 2020 to reach 6.6 million units, representing close to 9% of the global car market and more than tripling its year 2019 market share. Overall, EVs accounted for 17% of vehicle sales in Europe and 15% in France in 2021 (IEA,2022). While the electrification of the transport sector offers a good opportunity to reduce CO₂ emissions, a renewable energy source for EV charging and discharging, such as rooftop solar PV, should offer a better opportunity (Shepero et al., 2018). In this regard, an EV with a large battery capacity can store energy from the PV generation and later discharge that energy to meet household electricity demand through bidirectional charging (Kobashi

² Programmation pluriannuelle de l’énergie (PPE)

³ Stratégie Nationale Bas-Carbone (SNBC)

and Yarime, 2019). This is coined 'vehicle-to-home' (V2H) system. ⁴Bidirectional charging is an emerging technology with the potential to fast-track efforts to achieve net-zero emission homes. Bidirectional charging allows energy to flow in and out of an EV to support efficient energy utilisation (TotallyEV, 2022). Also, coupling rooftop solar PV and EV offers a great appeal from an environmental perspective. Since solar PV and EV prices are likely to keep falling, solar PV+EV coupling can play a key role in driving deep decarbonisation across multiple sectors and bring benefits through fuel diversification (for example, transport electrification with EVs), energy security, improved air quality, health and potential for productivity spillover from accelerated energy innovation (IEA, 2021d).

The building sector accounts for over 30% of global energy consumption and associated GHG emissions (Nazari et al., 2023). This means the sector requires a massive and innovative transition toward net-zero emissions (Ohene et al., 2022). In 2021, the EU proposed shifting to a zero-emission building target by 2030 to align with its long-term climate neutrality goal (Satola et al., 2022). Energy efficiency and renewable energy will play decisive roles in reducing GHG emissions in the building sector (Maduta et al., 2022). Increasing energy efficiency reduces fuel consumption and emissions (Shahsavari et al., 2022). Rooftop solar PV+EV coupling will provide co-benefits such as reduced ambient air pollution with significant health and economic benefits by stimulating new industrial capacities and job creation in clean energy and the engineering, manufacturing, and construction industries to complement their sustainable implementation. Clean energy technologies such as PV+EV will also provide significant opportunities by creating many new business opportunities and innovations (IEA, 2021d). Therefore, zero-emission buildings are a crucial component of the EU strategy towards climate neutrality, able to trigger additional benefits, such as resilience, recyclability, energy security, and health (Maduta et al., 2022). The joint decarbonisation of the energy, transport and building sectors can be pivotal in enabling France to meet its "Fit for 55" targets (Heinisch et al., 2021).

This paper uses the System Advisor Model (SAM) to run a techno-economic simulation of coupling rooftop solar PV+EV systems for residential buildings in France's three most populous cities (Paris, Marseille, and Lyon). SAM is a techno-economic software model that calculates the system performance and financial metrics of renewable energy projects (Nate et al., 2018). We attempt to answer the following questions:

- What is the decarbonisation potential of coupling rooftop solar PV+EV in France's cities?
- What are the potential implementation challenges and the policy choices needed to address them?

We contribute to the PV+EV coupling debate as follows: i. we apply an empirical context-specific case study using two commonly used vehicle models in France to illustrate how the PV+EV concept can be designed and contribute to the combined decarbonisation of France's transport, energy and building sectors. ii. we analyse the context-specific market design and regulatory issues of the rooftop solar PV+EV concept in France. This paper proceeds as follows. Section 2 discusses the material and methods. Section 3 discusses the theory and calculation. Section 4 presents the results. Section 5 discusses the potential implementation challenges and the policy choices needed to address them. Section 6 concludes the paper.

⁴ As of 2021, "CHAdeMO", developed by Japanese automakers, supports bidirectional charging. The latest versions of "CHAdeMO" and the Chinese "GB/T" protocol have been co-developed as a standard protocol, "ChaoJi" (called CHAdeMO3.0), to support bidirectional charging. In addition, the European and U.S. protocol, "CCS", plans to develop new versions with bidirectional charging capability by 2025 Kobashi et al. (2022).

2. Material and Methods

There are few studies on techno-economic simulation and emission reductions/analysis for rooftop solar PV+EV integration at a city scale. Studies at the city scale are important for comprehensive understanding, strategic planning, and robust policy formulation to facilitate informed decision-making. This section discusses our material and methods.

Kobashi et al. (2021), studied the rooftop solar PV+EV concept in eight Japanese cities and special wards. They found that implementing the concept can meet 53%-95% of electricity demand in the nine major Japanese urban areas by 2030. The authors also found that the CO₂ emission in the cities from vehicle use and electricity generation can be reduced by 54%-95%, with potential cost savings of 26-41%. In a related work, Kobashi et al. (2020a), found that CO₂ emissions from vehicle and electricity use in the cities can be reduced by 60%-74% if EVs replace the entire car fleet. Kobashi et al. (2020b), applied the solar PV+EV concept to the cities of Kyoto (Japan) and Shenzhen (China). They found that "PV + EV" becomes cost-effective towards the year 2030 in Kyoto compared to "PV only", "PV+battery", and "EV charge only" systems. Also, the authors found that "PV + EV" has the highest CO₂ emissions reduction potential of all the technology combinations in their analysis. In another study, Kobashi et al. (2022), found an 88% reduction in the CO₂ emission from electricity and gasoline consumption in Shinchi, Fukushima (Japan), while meeting 89% of electricity demand. Their findings suggest that residential buildings could play a key role in urban decarbonisation.

Dorouchi et al.(2018) found that including an EV in a building's energy supply increases the chances of getting closer to a net zero energy building. Chen et al. (2020), found that utilising off-peak electricity and solar PV through V2H can improve the utilisation rate of off-peak electricity and solar PV, with considerable economic benefits. The authors found that solar PV+EV can meet household electricity demand on sunny and cloudy days without additional grid electricity. Coffman et al. (2017), found that integrating solar PV in buildings makes EVs outperform internal combustion engine vehicles (ICEVs) in terms of lifetime greenhouse gas (GHG) emissions from a total cost of ownership (TCO) perspective.

Fretzen et al. (2021), studied direct charging of EV batteries with solar energy without stationary battery storage using Rotterdam (in the Netherlands) as a case study. The authors found that solar PV can provide 71%-92% of EV charging load in summer with coordinated charging. However, the lower solar irradiance in winter results in a broader range of possibilities (13%-76%). Heinisch et al. (2021), studied the consequences of integrating electric cars and buses into the energy system of Gothenburg city in Sweden. The authors found that up to 85% of the power demand for charging EVs is flexible and that smart charging strategies can facilitate 62% of the solar PV charging in the charging electricity mix, compared to 24% when cars are charged directly.

Borge-Diez et al. (2021), combined V2H and vehicle-to-building (V2B) in different scenarios, such as when the building workers own EVs and the energy recharged at the workers' homes at night is discharged to the commercial building during daytime working hours. The authors found better building energy efficiency, reduced peak demand, and increased use of EVs for workplace transportation. Buonmano et al. (2019), analysed the energy, environmental and economic performance of a future V2B scenario with buildings powered by integrated flat-plate photovoltaic/thermal collectors equipped with electric energy storage. The authors found a reduction in grid electricity demand corresponding to a 57% savings in primary energy and a 51% reduction in CO₂ emissions. Ren et al.(2022) optimised the

deployment of rooftop PV and batteries for achieving net-zero energy for electric bus transportation in Hong Kong. In sum, the few available studies in the literature on rooftop solar PV+EV integration at the city scale have been conducted on cities in Japan and China (Kobashi et al, 2021; 2020; 2020; 2022). The few papers on European cities (such as Rotterdam in the Netherlands and Gothenburg, Sweden) appear to focus on smart charging/charging coordination (Fretzen et al., 2021) and smart charging strategies (Heinisch et al., 2021).

This paper is a techno-economic study and emissions reduction/analysis of coupling rooftop solar PV+EV at a city scale for France. We focus our research on Paris, Marseille, and Lyon for the following reasons. First, the cities are the most populous in France, with a significant need for emissions reduction. Second, the cities are the main sources of electrical energy demand, with many rooftops for solar PV installation (Hosseini, 2019). Third, the cities offer a good representative sample of weather patterns in France. Paris in the north has an average annual temperature of 11.8°C, whereas Marseille, in the south, has an average of 15°C and Lyon, which is close to the centre of France, has an average of 12.8°C, which is close to the national average. Table 1 shows some descriptive data on the three cities. Also, this paper provides the contextual background for academics, policymakers, analysts, and other stakeholders about the rooftop solar PV+EV concept, the implementation challenges involved, and how to overcome these challenges to enable rapid decarbonisation of France's electricity and transport sectors.

	Paris⁵	Marseilles⁶	Lyon⁷
Population	2,138,551	868,277	518,635
Population density (thousands/km ²)	21,000/km ²	3,600/km ²	11,000/km ²
Passenger vehicles per capita	0.34 ⁸	0.30 ⁹	0.45 ¹⁰
Passenger vehicles	739,704	260,483	233,386
Latitude	48° 51' N	43° 17' N	45° 46' N
Latitude	48° 51' N	43° 17' N	45° 46' N
Longitude	2° 20' E	5° 22' E	4° 50' E

Table 1: Descriptive data on Paris, Marseille, and Lyon. Source: Authors' compilation.

3. Theory and Calculation

Following the methodology developed by Kobashi et al. (2020a), we run simulations and techno-economic analyses using the SAM model (version 2020.11.29) developed by the US National Renewable Energy Laboratory (NREL). We also build a model to compute the emissions reduction/analysis of the rooftop solar PV+EV concept for Paris, Marseille, and Lyon. We model three scenarios: 'PV only with 2019 pricing', which means running the simulations with the 2019 price forecast of the PV system excluding EV, 'PV only with 2030 projected pricing', which means running the simulations with the 2030 price forecast of PV system excluding EV and 'PV+EV with 2030 projected pricing' which means combining the 2030 price forecast of PV and EV systems. For each of the three scenarios, we consider four cas-

⁵ <https://en.wikipedia.org/wiki/Paris>

⁶ <https://en.wikipedia.org/wiki/Marseille>

⁷ <https://en.wikipedia.org/wiki/Lyon>

⁸ <https://www.leparisien.fr/economie/les-francais-toujours-aussi-accros-a-la-voiture-13-07-2019-8115909.php>

⁹ <https://www.linternaute.com/ville/marseille/ville-13055/aut>

¹⁰ <https://www.rue89lyon.fr/2016/01/11/si-lyon-bannissait-la-voiture-les-resultats-dune-enquete-sur-nos-deplacements/>

es: (1.) with a feed-in tariff, (2.) without a feed-in tariff, (3.) with utilisation of half of the available rooftop space, (4.) with utilisation of all the available rooftop space (see Figure 1). SAM's (open) source code repository is public and hosted at Github.com (SAM, 2020). Table 2 summarises the variables and subscripts used in our model.

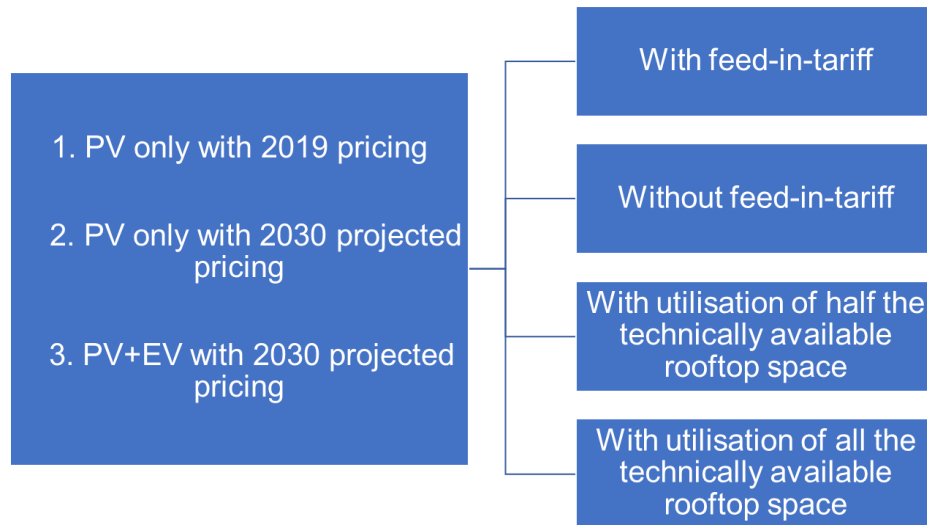


Figure 1: The three scenarios and four cases in our model

RAPC	rooftop area per capita (m ² /capita)
P _d	population density (Population/km ²)
E _{cost_{base}}	the electricity cost (grid electricity) without PV or EV battery
E _{cost_{sys}}	electricity costs with the renewable energies system, i.e. PV and EV operations and replacement cost (if any)
i	i-th city
pvcap	PV capacity (kW)
b	battery capacity (kWh)
t	project first year (year)
N	project period (year)
d _r	discount rate
E _{imp}	electricity imported from the grid (kWh/yr)
E _{exp}	electricity exported to the grid (kWh/yr)
T _{imp}	flat-rate electricity charge (\$/kWh)
T _{exp}	flat-rate feed-in tariff rebate (\$/kWh)
MR _{PV}	PV maintenance cost, including inverter replacement cost (\$/kWh/yr)
R _{bat}	EV battery replacement cost (\$/kWh).
Installed costs	initial investments or installed costs of the PV and EV battery systems.
C _{pv(t)}	cost of the PV system (\$/kW) in year t
C _{bat(t)}	cost of the battery system (\$/kWh) in year t
EV _{ad} (t)	EV additional costs (t) (\$/vehicle)
v	EV battery capacity (kWh/vehicle)
EV _{batcost} (t)	additional cost of EV battery purchase (\$/vehicle)
V2H _C (t)	V2H system costs (\$/vehicle)
t(i)	total number of passenger vehicles in the ith city
k(i)	annual average driving distance (km/vehicle/year) in the ith city

$g(i)$	gasoline efficiency for ICEV (l/km) in the i th city
$u(i)$	unit gasoline price (€/litre) in the i th city
$LCOE_{PV}$	levelised cost of energy of the PV system (kWh)
$LCOE_{EVb}$	levelised cost of energy of the EV battery system (kWh)
ΔIC	non-discounted incremental investment costs
ΔSUM	non-discounted sum of the net annual cashflow costs
t	time when the condition is satisfied for the first time.
$Elec_{PV}(i,pvcap,b)$	electricity generated by the PV (kWh/year) in the i th city
$E_{ld}(i,pvcap,b)$	total electricity load demand (kWh/year) in the i th city
$EMS_{base}(i)$	CO ₂ emissions in the base scenario for the i th city
$EMS_{sys}(i)$	CO ₂ emissions in the 'PV only' or 'PV + EV' scenarios for the i th city
$g(q)$	grid emission factor (kgCO ₂ /kWh) for the q th power utility
$n(i)$	total number of considered passenger vehicles in the i th city
$d(i)$	annual average driving distance (km/vehicle/year)
c	gasoline efficiency for ICEV (km/litre)
f	gasoline emission factor
$O\&M_{PV}$	Operation and Maintenance costs of PV

Table 2: Summary table of the variables and subscripts. Source: (Kobashi et al 2021; 2020b), IEA(2016)

First, we estimate the available rooftop area for Paris, Marseille, and Lyon based on research by the International Energy Agency (IEA, 2016). The IEA has found a positive correlation between rooftop area per capita of cities and population density with the following equation:

$$RAPC = 172.3 \cdot (P_d)^{-0.352} \dots\dots\dots 1$$

From the RAPC, we compute the city's total available rooftop space. We use 70% of the rooftop space to account for shading issues and legal and regulatory constraints (see section 3.2 for details). The city's total available rooftop space is an input into the SAM model. We then analyse the impact of the system using five indices: (a) NPV, (b) Levelized Cost of Energy (LCOE), (c) Payback Period, (d) Energy sufficiency, and (e) CO₂ emission reduction.

The NPV calculates the net savings of the project using discounted cash flows. The NPV can determine the technology or technologies combination with the highest financial return over time. The NPV of the project is composed of two parts: Electricity (NPV_e) and Gasoline (NPV_g). The gasoline part (NPV_g) is necessary for the 'PV + EV' system to calculate the NPV of replacing the ICEVs with EVs. We compute NPV_e using SAM, and calculate NPV_g separately from our model. We then sum the two NPVs to obtain the total NPV (NPV_t) as in equations 2 to 10 (Kobashi, 2020a).

$$NPV(pvcap,b,t) = \sum_{n=1}^N \frac{Cashflow(p,b,n,t)}{(1+dr)^n} - Installed\ Costs(pvcap,b,t) \dots\dots\dots 2$$

$$Cashflow(i,pvcap,b,n,t) = Ecost_{base}(i,n,t) - Ecost_{sys}(i,pvcap,b,n,t) \dots\dots\dots 3$$

$$Ecost_{base}(n,t) = E_{imp}(n,t) \cdot T_{imp} - Export(n,t) \cdot T_{exp} \dots\dots\dots 4$$

$$Ecost_{sys}(pvcap,b,n,t) = E_{imp}(pvcap,b,n,t) \cdot T_{imp} - E_{exp}(pvcap,b,n,t) \cdot T_{exp} + pvcap \cdot MR_{pv} + b \cdot R_{bat}(t) \dots\dots 5$$

$$Installed\ Costs(p,b,t) = pvcap \cdot C_{pv}(t) + b \cdot C_{bat}(t) \dots\dots\dots 6$$

$$C_{bat}(t) = EV_{ad}(t)/v \dots\dots\dots 7$$

$$EV_{ad}(t) = EV_{batcost}(t) + V2Hc(t) \dots\dots\dots 8$$

$$NPV_g(i,n,t) = \sum_{n=1}^N \frac{\text{Cashflow}_g(i,n,t)}{(1+dr)^n} \dots\dots\dots 9$$

where $\text{Cashflow}_g(i,n,t) = n(i).d(i).g(i).u(i)$

$$NPV_t = NPV_e + NPV_g \dots\dots\dots 10$$

The LCOE is the lifecycle cost per kilowatt-hour (kWh) of building and operating a power generation asset. The key inputs to calculate LCOE include investment costs, variable operation and maintenance (O&M) costs, fuel costs, financial costs, the plant's lifetime, electricity output, and system performance. Energy production is calculated based on lifetime, location, weather conditions, module efficiency, installation specification, and system performance (Yu, 2018).

$$\text{LCOE of PV system with EV battery} = \text{LCOE}_{PV} + \text{LCOE}_{EVb} \dots\dots\dots 11$$

$$\text{LCOE of PV system with EV battery} = \frac{\sum_{t=1}^n \frac{I_{PV+O\&M}^t}{(1+dr)^t}}{\sum_{t=1}^n \frac{Elec_{PV}^t}{(1+dr)^t}} + \frac{\sum_{t=1}^n \frac{I_{bat}^t}{(1+dr)^t}}{\sum_{t=1}^n \frac{Elec_{PV}^t}{(1+dr)^t}} \dots\dots\dots 12$$

The payback period is the duration in years from the initial investment to when the following condition is satisfied (Kobashi et al, 2022).

$$\text{Payback period} = \sum_{n=1}^t \Delta IC_n \leq \sum_{n=1}^t \Delta SUM_n \dots\dots\dots 13$$

Energy sufficiency defines how the electricity production of rooftop solar PV in the city compares to the annual energy demand (Kobashi et al, 2021).

$$\text{Energy sufficiency} = \text{ENS}(i,pvcap,b) = \text{Elec}_{PV}(i,pvcap,b) / E_{id}(i,pvcap,b) \dots\dots\dots 14$$

CO₂ emission reduction is the total percentage reduction in emissions from the rooftop solar PV or the 'PV+EV coupling'. It is expressed as:

$$\text{EMS}_{base}(i) = g(q).E_{imp} + t(i).k(i).c.f. \dots\dots\dots 15$$

$$\text{EMS}_{sys}(i) = g(q).E_{imp} \dots\dots\dots 16$$

$$\text{CO}_2 \text{ emission reduction}(\%) = (1 - \text{EMS}_{sys}(i) / \text{EMS}_{base}(i)) \cdot 100 \dots\dots\dots 17$$

3.1 The System Advisor Model (SAM)

SAM is a techno-economic model that calculates system performance and financial metrics of renewable energy projects. SAM's simulation model (Figure 2 - left in blue) makes calculations of a power system's electrical output and generates time series data representing the system's electricity production over a year. The simulation model takes the weather data/resource as the input data for a location, information on the system's specifications, and losses to compute the system's electricity production (Nate et al, 2018).

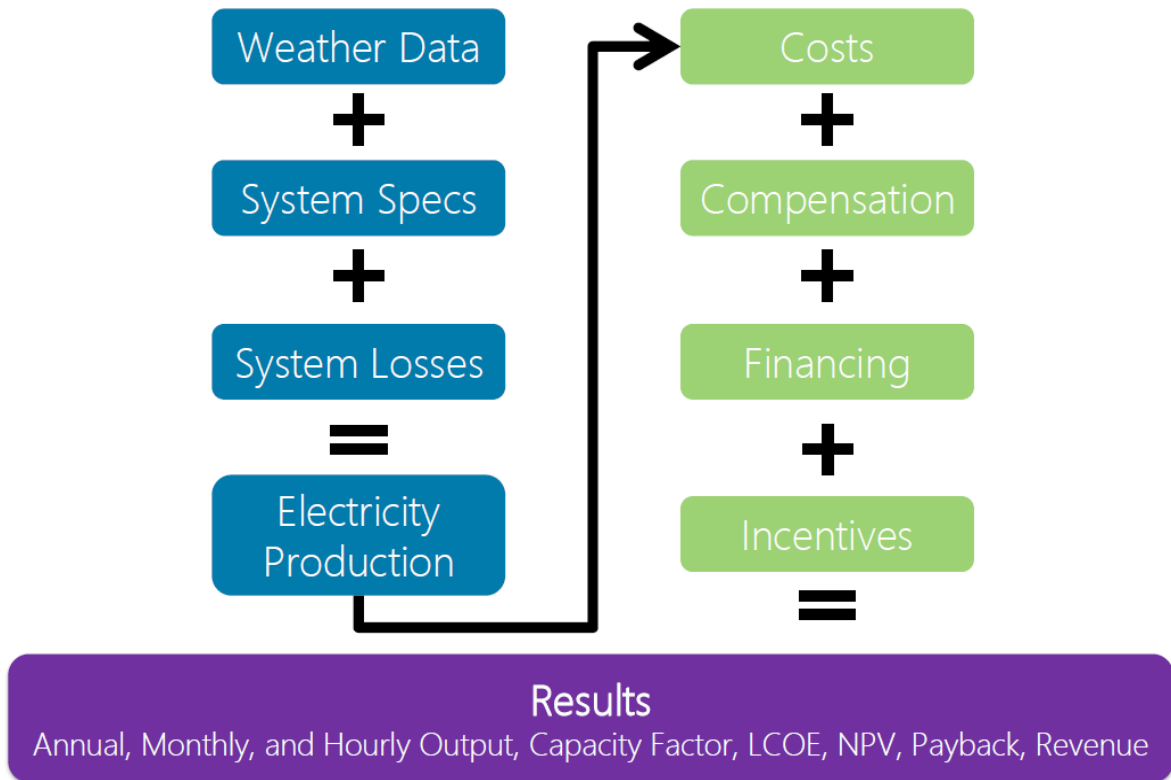


Figure 2: Schematic description of the System Advisor Model (SAM). Source: Freeman (2020)

The financial model (Figure 3 - right in green) computes the financial metrics for projects based on the cash flow and electrical output calculated from the simulation model over a specified period of analysis. Then, the simulation model is combined with the financial model starting from the cost of a given system and the compensation for the system. The output is combined with consideration for the system financing (such as equity and debt) and the incentive the system may be eligible for at federal, state, or local levels. The results are annual, monthly, and hourly output, NPV, LCOE, and payback period (Freeman (2020), NREL (2020)).

3.2 Data source and model assumptions

The viability of renewable energy projects depends on a range of factors treated as exogenous parameters. These include the PV and battery system costs, electricity tariffs, project period, electricity demand profile, variable PV generation, PV and battery systems degradation, electricity losses, discount rate, and local weather conditions (Kobashi et al, 2022). We use these parameters, among others, as input data in our model. Table 3 summarises our data and sources. Figures 3,4 and 5 show the hourly power demand for Paris, Marseille, and Lyon, respectively.

Table 3: Input data and sources

	DATA	SOURCE
Paris, Marseille, and Lyon	Hourly power demand 2019 (8760 timesteps)	Réseau de Transport de l'électricité (RTE, 2019a)

Paris, Marseille, and Lyon	Solar resource data and ambient weather conditions for Paris, Marseille, and Lyon in 2019	NREL (USA) National Solar Radiation Database ¹¹ (NSRDB, 2021)
Paris, Marseille, and Lyon (70% of rooftop space available for solar PV installation at half capacity)	Paris (3.948 km ²) Marseille (2.933 km ²) Lyon (1.183 km ²)	Computed from mathematical equations) (IEA, 2016)
Installed cost of rooftop solar PV (2019)	\$ 2.72/Wdc	NREL (USA) (NREL, 2020)
Projected installed Cost of rooftop solar PV (2030)	\$ 1.83/Wdc	NREL (Ardani et al, 2018)
Household electricity tariff	17.99 c€/kWh	Statista (2021a)
Residential rooftop solar PV feed-in tariff in France	9.62 c€/kWh	Statista (2021b)
Price for rooftop solar PV producer PV installation of >=3kWp	A producer receives 18.49c€/kWh. If he sells all his production or 10 c€/kWh if he sells only the surplus	Ministry of Economy, Finance, and Recovery (MEFR, 2021)
Cost of EV+ V2H system in 2030 for the modelled scenario of 50% of EVs & 50% EVs battery capacity at a battery cost of 15-20% of total EV cost	€ 147/kWh	Authors' computation
Renault Zoe battery capacity	52kWhr	Renault (2021)
Cost of EV - Renault Zoe 52kWh battery, range - 395km (€32500 minus €6000 ecology bonus)	€ 26,500	Renault (2021)
Cost of a comparable ICEV (Twingo) - Twingo is the cheapest comparable ICEV at €13,450.	€ 13,450	Renault (2021)
Annual driving distance in France per passenger vehicle (2018)	13,117 km/vehicle	STATISTA (2021c)
PV maintenance cost	29 \$/kW/year	NREL (2020)
Project period	20 years	Ministry of Economy, Finance, and Recovery (MEFR, 2021)
Discount rate	3%	Thebault & Gaillard (2021)
Gasoline efficiency of passenger cars	0.072 litre/km	IEA (2021)
Electrical efficiency of EVs	5.3 km/kWh	Kobashi et al. (2021)
Unit gasoline price (unleaded petrol octane-95)	1.57 €/litre	Global prices (2021)
CO ₂ emissions from gasoline	6.72 kgCO ₂ /litre	GHG (2019)
Emissions from electricity generation in 2019 and 2030 projection	57.3g/kWh CO ₂ eq (2019) 33.9g/kWh CO ₂ eq (2030)	Statista (2022b)
Speed of Passenger vehicles in France on different types of roads	84.29 km/hour	Statista (2021d)
Average daily driving distance of passenger vehicles	35.94 km/vehicle-day	Authors' computation
Average daily driving time	0.43 hours/vehicle-day	Authors' computation
Average gasoline consumption	945.03 Litre/year/vehicle	Authors' computation
Annual spending on gasoline	€1,483.70 /year/vehicle	Authors' computation
Total EV battery capacity with 50% EV penetration@50% capacity	Paris (9.62 GWh) Marseille (3.39 GWh) Lyon (3.03 GWh)	Authors' computation

¹¹ The solar resource data for Paris, Marseille and Lyon are in Annex B of this manuscript

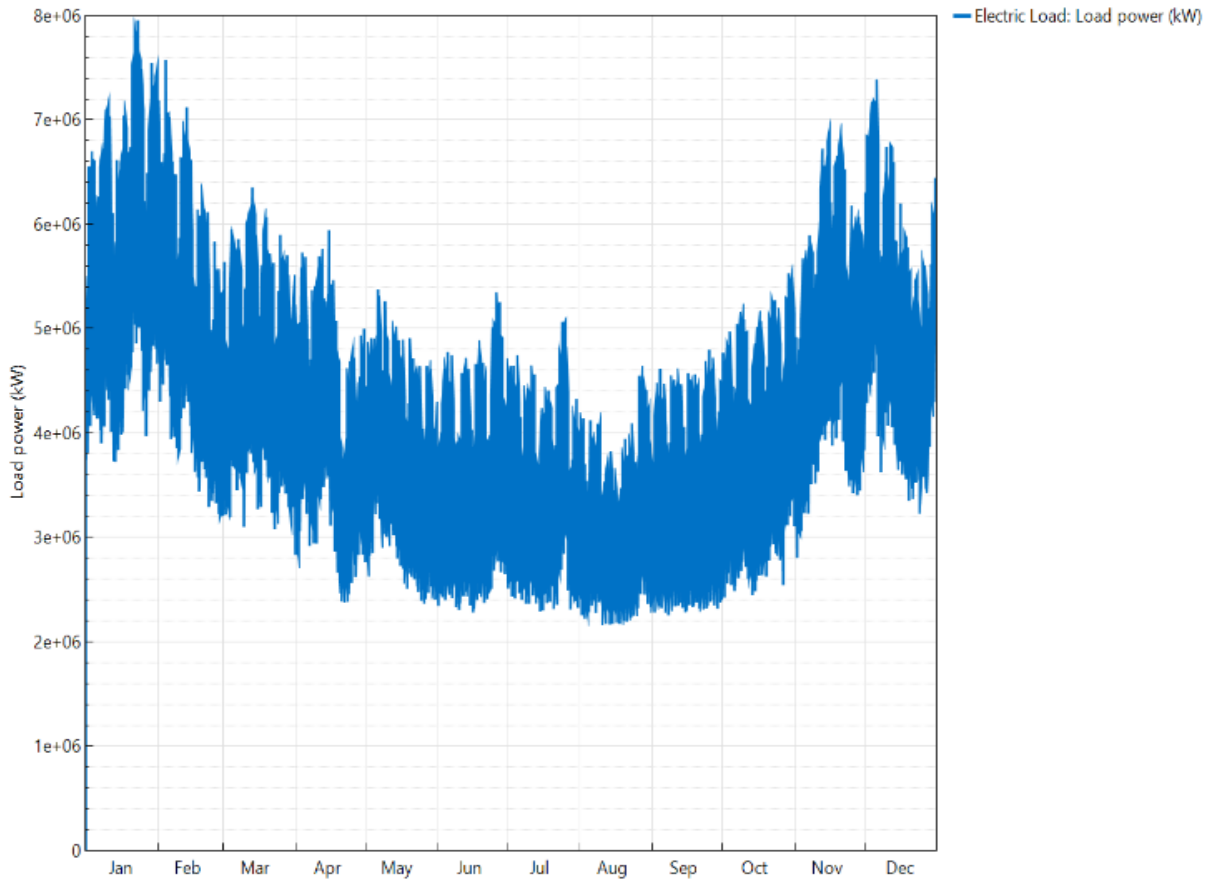


Figure 3: Hourly power demand for Paris in 2019 (showing the highest load of 7,919MW and the lowest load of 2,296MW)

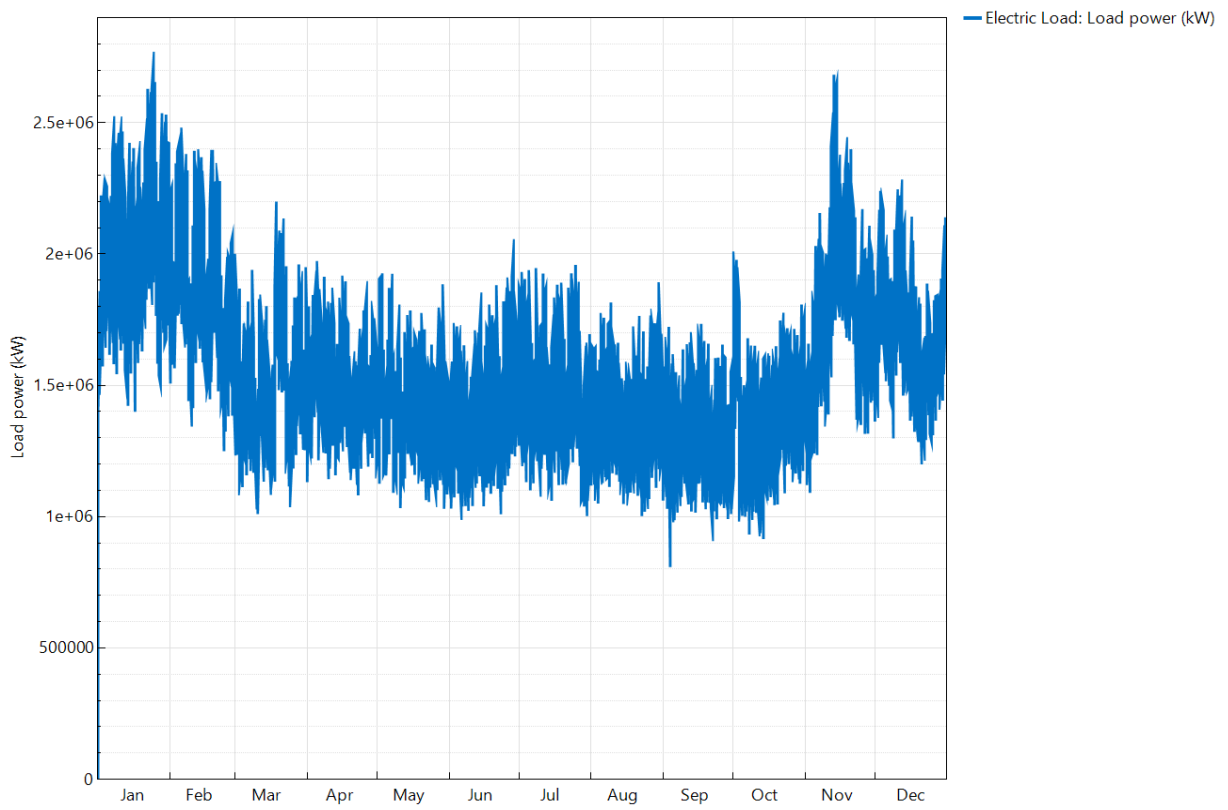


Figure 4: Hourly power demand for Marseille in 2019 (showing the highest load of 2,719MW and the lowest load of 860MW)

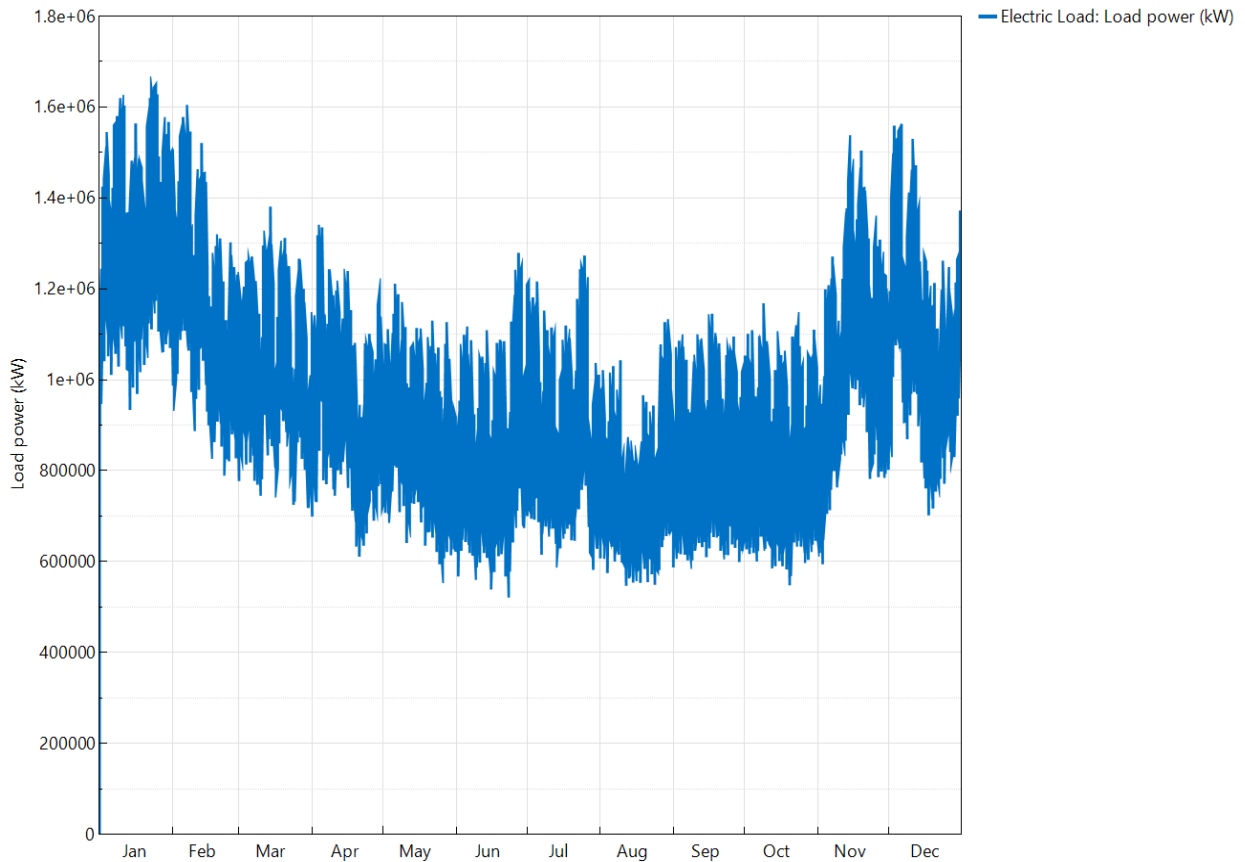


Figure 5: Hourly power demand for Lyon in 2019 (showing the highest load of 1,648MW and the lowest load of 553MW)

The model requires a weather file for each city with temperature, global horizontal irradiance, direct normal irradiance, and diffuse horizontal irradiance data in order to calculate the hourly power generation by solar PV panels in a city (Kobashi et al., 2021). We use the solar resource and ambient weather conditions data from the US National Solar Radiation Database (USRDB, 2021). We account for external shading losses (shading of beams and diffuse incident irradiance from nearby objects such as trees and buildings) and legal and regulatory constraints by assuming that 70% of the rooftop space in the cities is technically available for rooftop solar PV installation. Shading from neighbouring buildings affects a building's available solar radiation and PV power generation (Kobashi et al., 2021; 2022). Also, legal and regulatory constraints affect some buildings or locations where rooftop solar PV installations are forbidden by law or regulation(s). With the utilisation of 70% of the available rooftop space and half of the available space for the solar PV installation, we compute 3.95km², 2.93km², and 1.18km² available roof space for Paris, Marseille, and Lyon, respectively.

The total installed cost of rooftop solar PV includes direct capital costs such as the module and inverter prices, the balance of system equipment cost, the installation's labour cost, the installer's margin, overheads, and DC battery capacity costs. The indirect capital costs are permitting and environmental studies, engineering costs, and the developer's overhead. We combine these direct and indirect costs to compute the total installed cost of US\$ 2.72/Wdc for 2019 from SAM (NREL, 2020). We use the projected installed cost of rooftop solar PV

(including roof replacement) of US\$ 1.82/Wdc for 2030 for a 'less aggressive' falling solar PV price scenario from NREL (Ardani et al. 2018)

We use the data from Statista for the household electricity tariff of 17.99 c€/kWh (assuming a flat rate) and the residential rooftop solar PV feed-in tariff of 9.62 c€/kWh for France (Statista (2021a, 2021b)). We use a PV maintenance cost of \$29/kW/year from SAM and a real discount rate of 3% (Thebault and Gaillard 2021), an inflation rate of 2%, and a nominal discount rate of 5%. France offers feed-in tariffs for small-scale solar PV (up to 100-kilowatt peak [kWp] on rooftops) serving individual and collective self-consumption. Based on the data from the French Ministry of Economy, Finance, and Recovery (MEFR, 2021); we use the applicable rooftop solar PV price regime for rooftop solar PV producers. A producer receives 17.89c€/kWh if he sells all his output or 10c€/kWh if he sells only the surplus, with a project period of 20 years (MEFR, 2021). Net metering is not allowed under this scheme. The electricity market regulator (CRE) regulates a specific grid tariff for self-consumption, notably for collective users (IEA, 2021a). We model EV charging with a focus on homes with PVs only. We model the V2H system as benefitting the associated single home and the grid such that when there is excess production, the system can export (sell) power to the grid at 10 c€/kWh based on the government's regulatory tariffs. When there is insufficient production, the system can import (buy) power from the grid at the household electricity tariff of 17.99 c€/kWh.

Moreover, we model the desired bank power based on the maximum possible power output using the SunPower mono-crystalline silicon solar PV panel based on a module area of 1.631m² per panel, a maximum power capacity of 335.2W per panel, a panel efficiency of 20.55% and a total irradiance of 1000W/m² at 25°C. Our model considers electricity losses, such as soiling (5%) and DC power losses (4.4%). The DC power losses include DC wiring (2%), diodes and connections (0.5%), and module mismatch (2%). The AC losses include wiring (1%) and an inverter efficiency loss of 2.9% (NREL, 2020).

For the EV, we use the Renault Zoe, one of the cheapest and best-selling EVs in France Statista (2020a) with a battery capacity of 52kWh, a range of 395km, and a price of € 26,500 (i.e., €32,500 minus the government's €6,000 ecology bonus/subsidy) (Renault, 2021). We use the data for the annual driving distance for all the passenger cars (13,117 km/vehicle) (Statista, 2021c) to compute the average speed of passenger vehicles (84.29 km/hour) on the different types of roads in France (Statista, 2021d). Thus, we compute France's average daily (35.94 km/vehicle-day) and hourly (0.43 hours/vehicle-day) driving distance. This implies that, apart from transportation, passenger cars in France (on average) are potentially available (about 98% of the time) for a secondary function, such as powering a V2H system. Our finding is consistent with the status quo in many developed countries such as the US (96% of the time) (Kempton and Tomic, 2005), Japan (98% of the time) (Kobashi et al, 2021) and the UK, Germany, and Italy (above 95% of the time) (Pasaoglu et al, 2014). Furthermore, if we suppose the EV covers an average of about 36km per day at an average efficiency of 5.3 km/kWh or 18.86kWh per 100km (Kobashi et al, 2020a), then the EV will require a 6.8kWhr battery capacity for 36km per day. In other words, by charging the EV battery to the upper charge limit of 90% capacity.¹², we have a usable capacity of 13kWh for driving before recharge. Therefore, we assume that 26kWhr of the Renault Zoe battery capacity is available for the V2H system. A 26kWh battery capacity per day is equivalent to

¹² A charge from 0-100% shown by the EV is typically a charge from 15-90% of the battery (a common practice by manufacturers to avoid battery degradation) (Nuvve, 2021)

9,490kWh per year (or twice the average French household yearly energy demand of 4,745kWh (Selectra, 2021)).

We compare the Renault Zoe to a Renault Twingo (one of the cheapest ICEVs in France, at €13,450). The price difference between the Renault Zoe (at €26,500) and a Renault Twingo is €13,050. We assume a gasoline efficiency of 0.072 litres/km (IEA, 2021b), a unit gasoline price (of unleaded petrol octane-95) of €1.57/litre (global prices, 2021), and ICEV CO₂ emissions of 6.72 kgCO₂/litre (GHG, 2019). Based on Statista's data, the power sector in France emitted 57.3g of CO₂ per kilowatt-hour (gCO₂/kWh) from electricity generation in 2020¹³ and is projected to emit 33.9 gCO₂/kWh in 2030 (Statista, 2022b). From the preceding data, we compute an average yearly ICEV gasoline consumption of 945litres/year/vehicle and annual spending on gasoline of €1,483/year/vehicle. We use the input data to compute the NPV of gasoline (equation 9), the total NPV (equation 10), and the CO₂ emissions reduction potential of the rooftop solar PV+EV concept (equation 15). We assume a financial leverage ratio of 4:1 in our model.

To compute the cost of the EV+V2H system by 2030, we assume that half of the ICEVs will be replaced by EVs by 2030, and half (26kWh) of Renault Zoe's battery capacity is used for the V2H system. We assume a 0.5% yearly price increase for the ICEV to obtain a cost of €14,067 for a Renault Twingo by 2030. We assume a Renault Zoe will be 15% cheaper at €11,957 than a Twingo in 2030. These assumptions are premised on the fact that battery electric vehicles (BEVs) are expected to achieve price parity with the equivalent ICEVs in all the light-vehicle segments in Europe by 2025. Price parity is reached in the year at which a BEV becomes cheaper than the equivalent ICEV. According to BNEF (2021), EV adoption is expected to speed up from 2025 as the different segments hit price parity quickly and more EV models are launched. Figure 6 illustrates an ICEV with about a €13,000 price difference from an EV in 2021, reaching price parity by 2025 and becoming 10%-20% cheaper than the ICEV by 2030. This price difference is similar and comparable to the Renault Zoe vs Renault Twingo price difference of €13,050 in 2021 in our model.

¹³ We use 57.3gCO₂/kWh from 2020 for 2019 in our model.

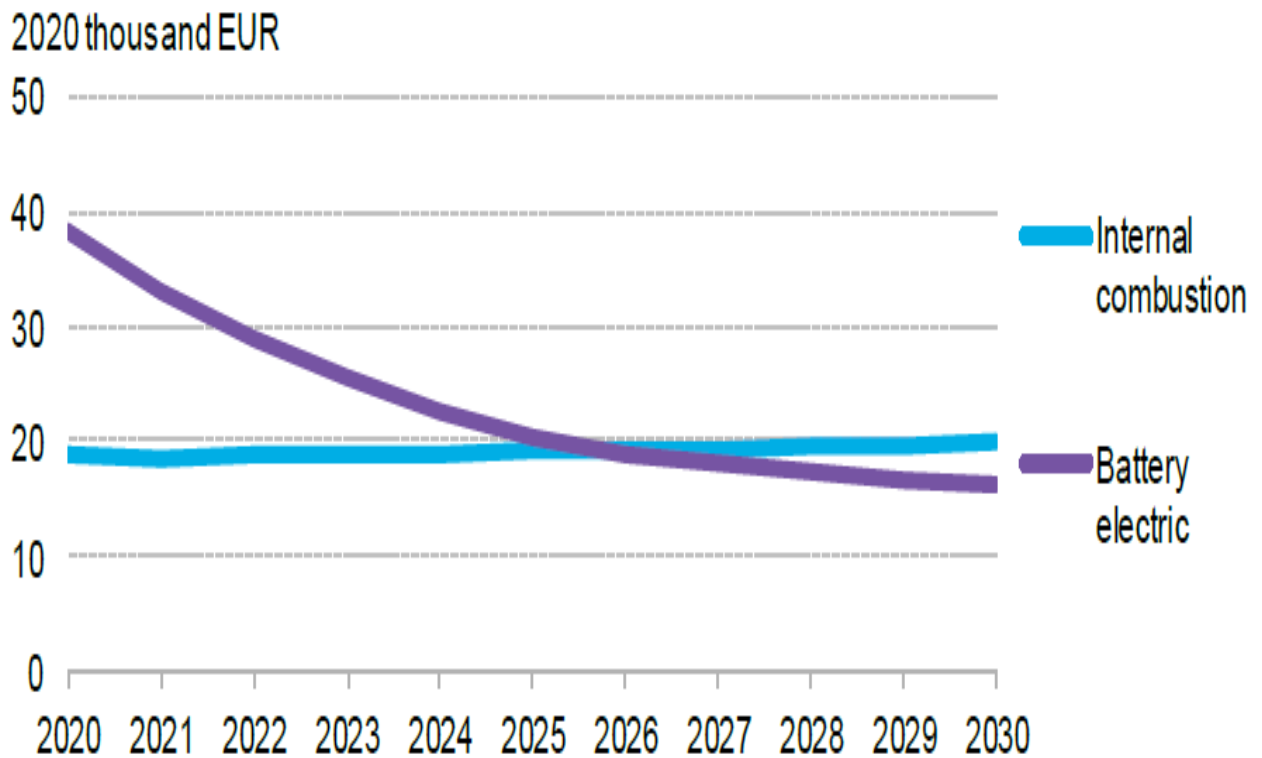


Figure 6: EV vs ICEV price parity projection Source: BNEF (2021)

EV uptake in Europe is set to explode with more extensive choices of EV models. The emission regulations and other government initiatives aimed at phasing out ICEVs and driving EV adoption should enable EVs to reach cost parity with equivalent ICEVs within three years (Oil price, 2022; BNEF, 2021).

Furthermore, according to BNEF (Figure 7), BEVs are expected to represent 51% of new passenger vehicle sales in Western Europe by 2030 in the base case. Moreover, according to the IEA's 'net zero emissions by 2050 scenario' (IEA, 2021c), by 2030, there will be over 300 million electric cars on the road globally, accounting for over 60% of new car sales (IEA, 2021c; IEA, 2021d). Also, in the SNBC, the French government projects a 35% share of electric cars and another 10% for hybrid cars in new vehicle sales, 45% in total by 2030 (IEA, 2021a). Therefore, our assumptions that half of the ICEVs fleet will be replaced by EVs in 2030 and that EVs will be 15% cheaper than ICEVs by 2030 are consistent with the IEA and BNEF projections and within the range of the French government's (SNBC) policy target.

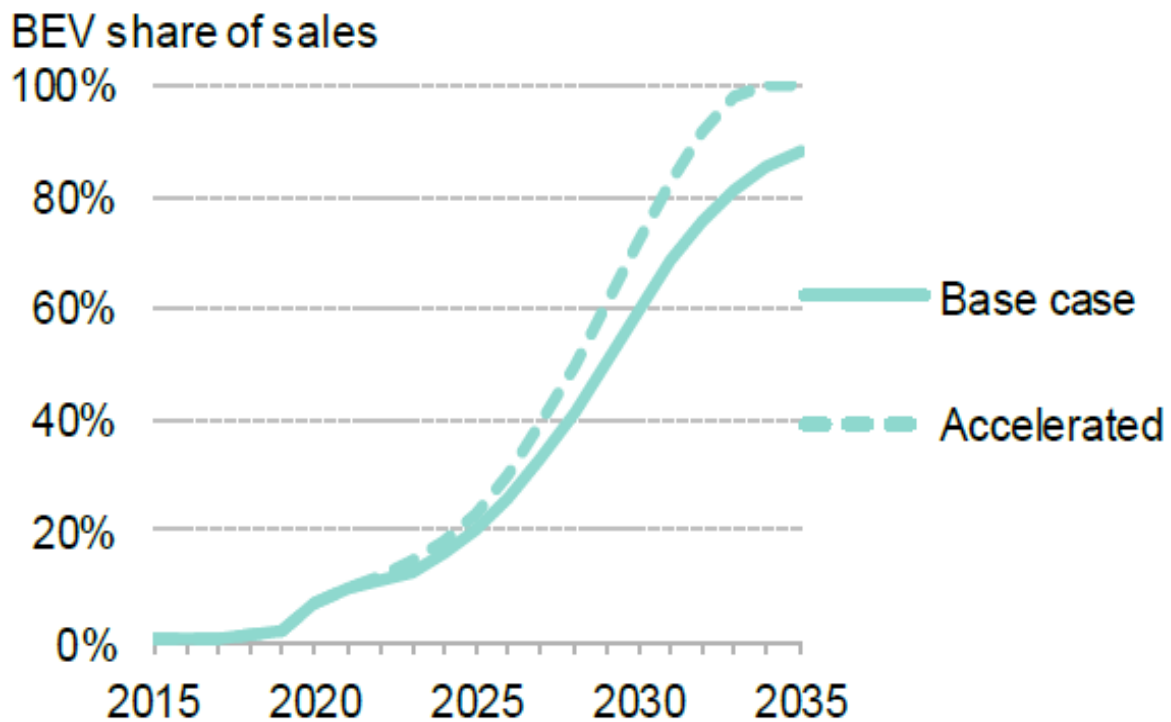


Figure 7: Projected share of BEVs in total car sales for 2030. Source: BNEF (2021)

Also, we assume that the EV battery will be 15-20% of the total EV cost by 2030 (Statista, 2020b). Battery technology is improving rapidly, leading to lower prices and increased competition in Europe. New chemistries, better manufacturing methods, innovative cell and pack design concepts, and other factors will reduce average prices per kilowatt-hour by a projected 58% from 2020 to 2030 (BNEF, 2021). Based on our data, we compute the additional cost of the EV battery capacity (i.e., half of the EV battery capacity and half of the passenger vehicles replaced in the cities) plus the cost of the V2H system.

To compute the cost of the V2H system, we estimate the quantity required per city based on the average national housing occupancy ratio. Of the 35.4 million total housing stock units in France, 19.7 million (56%) have single owners, and 15.66 million (44%) are collective/shared housing units (Statista, 2022a). Therefore, we estimate one V2H per single-owner building and one V2H for a collective building assuming two EV owners. Consequently, we assume two V2H systems for every three EVs. Each V2H system is projected to cost €2,440 by 2030 (including the installation cost) (Kobashi et al., 2021). In sum, we estimate a total additional cost for EV battery plus V2H systems of about €147/kWh using the national data as a proxy to estimate the number of V2H systems for the three cities. This estimate simplifies the challenge of estimating the additional costs of the V2H system. We do not use the total cost of the EV because households buy EVs to commute as a primary function. The use of EVs to meet household electricity demand is secondary. This potential secondary function is possible because EV is idle for over 95% of the time, as discussed earlier. However, we have added the EV battery cost to the V2H system cost to be conservative.

We conduct a sensitivity analysis on some of the key input variables in our model to understand the uncertainty of the EV battery+V2H costs and other exogenous input data on our results.

3.3 Boundary of our model

To simplify our model, we consider EV charging at home only (no grid charging of the EV battery). In addition, we exclude parking lots or roadway spaces as potential locations for rooftop solar PV installations because we do not have the data. Furthermore, we exclude the potential benefits of using the EV for other ancillary grid services, such as vehicle-to-grid (V2G). Also, we assume that one ICEV is replaced with one EV per person (in some cases, households have more than one ICEV). Based on the findings of (Nuvve, 2021) on time to end-of-life analysis of an EV battery, we assume there will be no need for a battery replacement if the EV owners avoid fast charging. The average temperatures of Paris (11.8°C), Marseille (15°C), and Lyon (12.8°C) should enable the EV battery to last for the 20 years project period with an optimal home charging strategy.

In addition, we compute the CO₂ emissions from gasoline combustion and grid electricity generation. We exclude the CO₂ emissions from other processes, such as producing/disposing of the battery, PV panels, ICEV, and EV CO₂ emissions. Although an EV is less CO₂ emitting in its life cycle than an ICEV with cleaner electricity generation (i.e. over 90% of the power generation in France (Figure 8), it is still necessary to have zero emissions for the process of producing and disposing PVs and EVs in order to meet global net-zero emission (Kobashi et al, 2021).

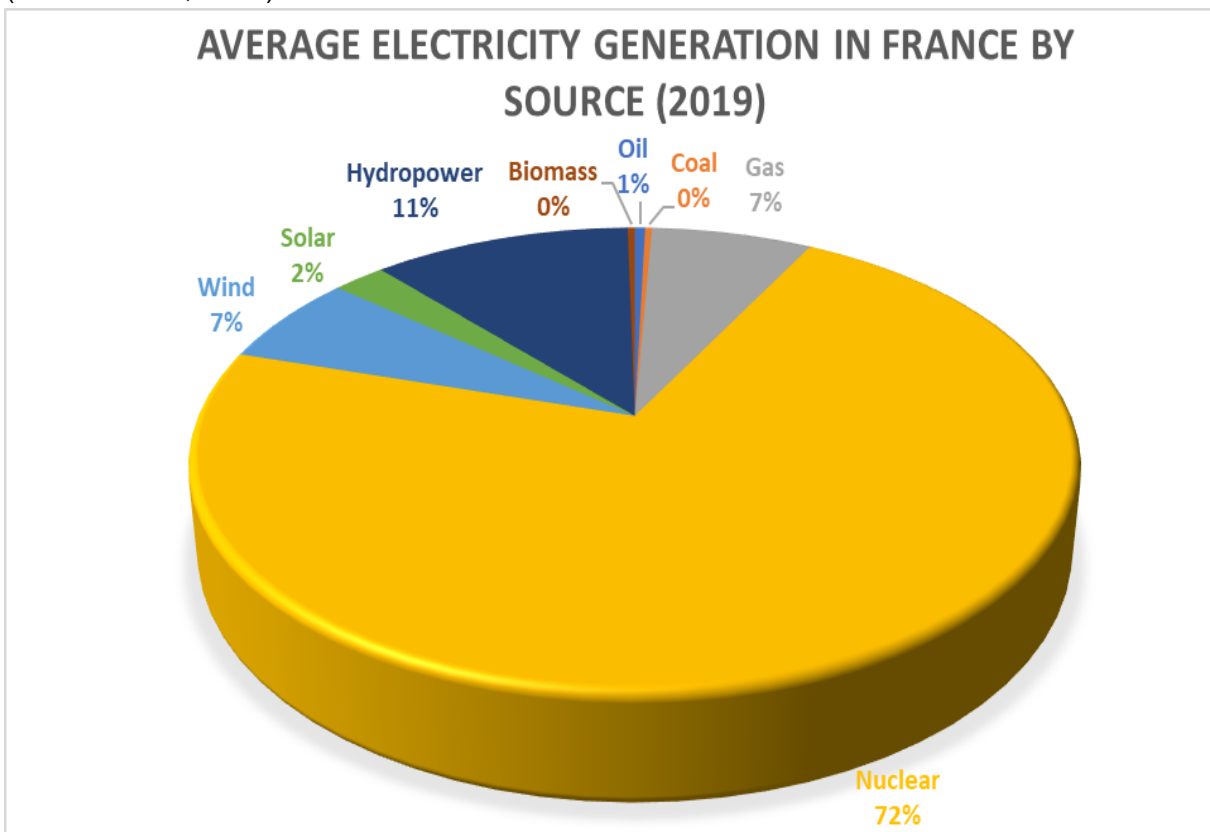


Fig 8: Power generation by energy source in France. Authors' computation with data from RTE (2019)

Finally, we do not consider the difference in operation and maintenance costs between ICEV and EV that could further enhance the economic benefits of rooftop Solar PV+EV (Kobashi et al, 2021).

4. Results

This section presents the results of our analyses. Table 4 summarises our simulation results for the utilisation of half of the rooftop space in Paris, Marseille, and Lyon for the different scenarios: 'PV only in 2019', 'PV only with 2030 projected pricing', and 'PV+EV with 2030 projected pricing' (with and without feed-in tariffs).

For the 'PV only in 2019 without a feed-in tariff' scenario, the NPV is € -533million for Paris, €940 million for Marseille, and €80 million for Lyon. The PV only system can achieve an energy sufficiency of 1.81% in Paris, 6.43% in Marseille, and 3.19% in Lyon. Marseille has the lowest LCOE of €0.21/kWh and the earliest payback period of 8.6 years, followed by Lyon with an LCOE of €0.27/kWh and a payback period of 11.5 years, and Paris with an LCOE of €0.36/kWh and a payback period of 16.1 years. In terms of CO₂ emissions reduction, the 'PV only' system can save about 15,800, 39,600 and 51,200 tons of CO₂ in Lyon, Paris, and Marseille, respectively. Overall, Marseille provides the best results (Table 4.1), which is expected as Marseille's location in the south of France has higher solar irradiation/ambient temperatures.

For the 'PV only with 2030 projected pricing' without a feed-in tariff scenario, the NPV is €305 million for Paris, €1.56 billion for Marseille, and €332 million for Lyon. The PV system can achieve an energy sufficiency of 1.81% in Paris, 6.43% in Marseille, and 3.19% in Lyon. Marseille has the lowest LCOE of €0.15/kWh and the earliest payback period of 5.8 years, followed by Lyon with an LCOE of €0.19/kWh and a payback period of 7.8 years, and Paris with an LCOE of €0.26/kWh and a payback period of 10.8 years. This result implies that the 'PV only in 2030 system' can be competitive in Lyon and Marseille compared to the projected grid electricity price (with a current price of around €0.18/kWh and assuming a 2%-4% annual increment) in France. However, its energy sufficiency is relatively low. In terms of CO₂ emissions reduction, the system can save about 9,300, 23,400, and 30,300 tons of CO₂ in Lyon, Paris, and Marseille, respectively. Marseille again provides the best results (Table 4.2).

Table 4: Simulation results

4.1 "PV only" in 2019 (without a FIT)	Paris	Marseille	Lyon
NPV (€ Million)	-533.90	940.78	80.64
Energy sufficiency (%)	1.81	6.43	3.19
CO2 emissions reduction (Tonnes)	39,675.30	51,258.65	15,807.76
Payback period	16.1 years	8.6 years	11.5 years
LCOE (€/kWh)	0.36	0.21	0.27
IRR (%)	-20.34	48.25	10.25
4.2 "PV only" in 2030 (without a FIT)	Paris	Marseille	Lyon
NPV (€ Million)	305.06	1564.05	332.03
Energy sufficiency (%)	1.81	6.43	3.19
CO2 emissions reduction (Tonnes)	23,472.82	30,325.80	9,352.23
Payback Period	10.8 Years	5.8 years	7.8 years
LCOE (€/kWh)	0.26	0.15	0.19
IRR (%)	17.30	119.43	62.85
4.3 "PV + EV" in 2030 (without a FIT)	Paris	Marseille	Lyon
NPV (€Million)	19,111	11,596	5,971
Energy sufficiency (%)	19.70	42.58	26.88
CO2 emissions reduction (%)	43.46	48.35	46.18

CO2 emissions reduction (Tonnes)	2,603,793	1,028,050	819,829
Payback period	3 years	2.1 years	3 years
LCOE (€/kWh)	0.037	0.027	0.037
IRR (%)	183.25	328.88	182.82
4.4 "PV only" in 2019 (with FIT)	Paris	Marseille	Lyon
NPV (€Million)	-0.53	1,858.07	363.44
Energy sufficiency (%)	1.81	6.43	3.19
CO2 emissions reduction (Tonnes)	39,675.30	51,258.65	15,807.76
Payback period	11.2 years	5.5 years	7.3 years
LCOE (€/kWh)	0.273	0.120	0.184
IRR (%)	-0.02	95.30	46.21
4.5 "PV only" in 2030 (with FIT)	Paris	Marseille	Lyon
NPV (€Million)	1,014.58	2,481.34	614.83
Energy sufficiency (%)	1.81	6.43	3.19
CO2 emissions reduction (Tonnes)	23,472.82	30,325.80	9,352.23
Payback period	6.7 years	3.7 years	4.9 years
LCOE (€/kWh)	0.171	0.062	0.107
IRR (%)	57.55	189.47	116.39
4.6 "PV + EV" in 2030 (with FIT)	Paris	Marseille	Lyon
NPV (€Million)	26,908.86	17,733.52	8,378.44
Energy sufficiency (%)	19.70	42.58	53.34
CO2 emissions reduction (%)	43.46	48.35	46.18
CO2 emissions reduction (Tonnes)	2,603,793	1,028,050	819,829
Payback period	1.5 years	1 year	1.5 years
LCOE (€/kWh)	-0.05	-0.06	-0.05
IRR (%)	333.67	574.72	332.58

For the "PV+EV with 2030 projected pricing" without a feed-in tariff case (Table 4.3), we will discuss the result in more detail per city. Figures 9,10, and 11 show the simulation results for electricity generated from the system, load, and battery discharge to the load.

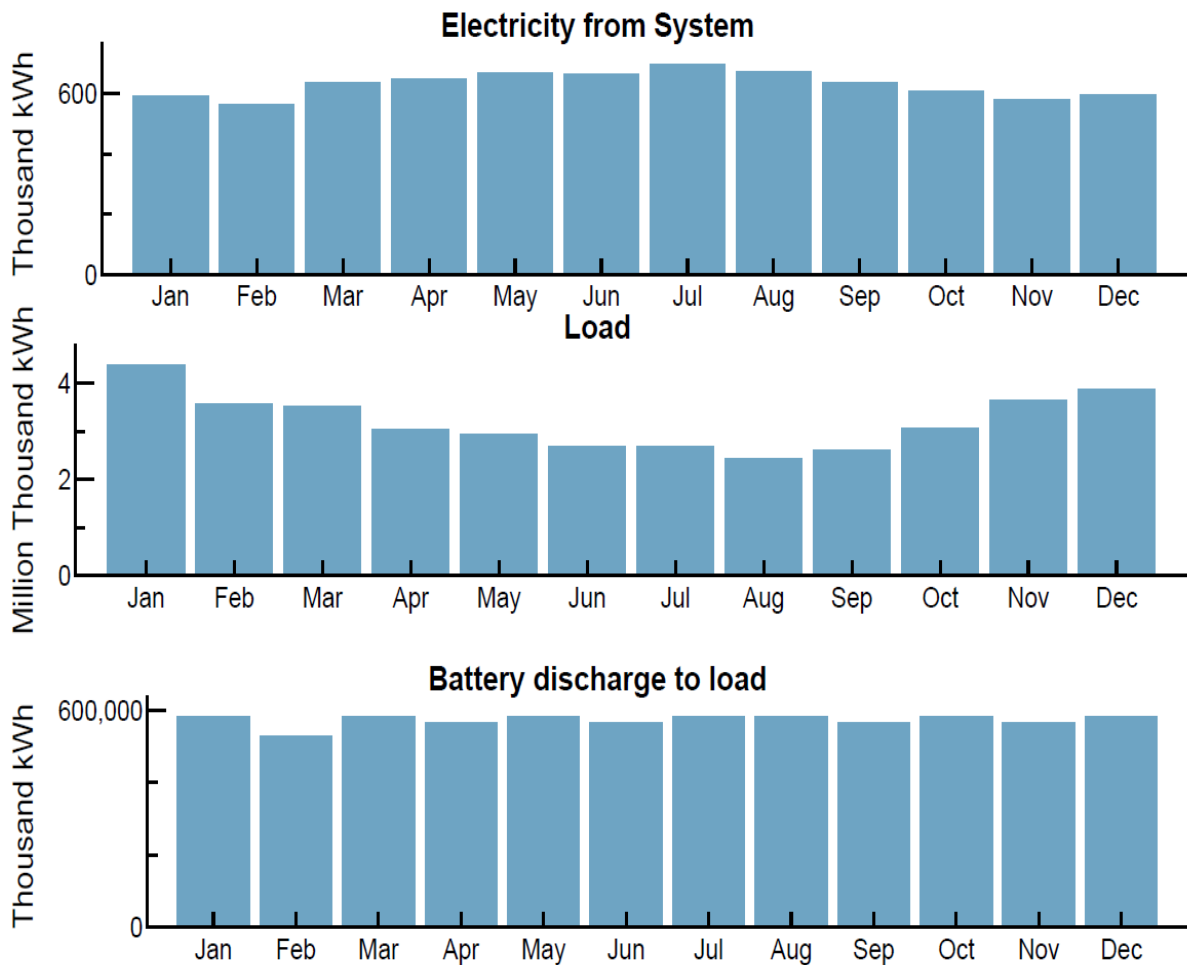


Figure 9: Simulation results of the monthly generation & load summary of solar PV and EV generation & total load for Paris

- *Paris*

Our result shows that if rooftop solar PV is installed on half of the available roofs, and if half of the passenger vehicle owners replace their ICEVs with EVs by 2030 and use 26kWh (50%) of the EV battery capacity coupled with the rooftop solar PV, then the concept can :

- Save 2.7million tons of CO₂eq emissions (40%) from electricity generation and passenger vehicle transportation per year.
- Generate 7.5TWh out of the 38.1TWh total annual demand (not only residential load) for Paris (an energy sufficiency of 19.7%).
- Be a potentially worthwhile investment with a payback period of 3 years, an LCOE of €0.037/kWh, and an NPV of €19.1 billion without a feed-in tariff by 2030.

- *Marseille*

Our result shows that if rooftop solar PV is installed on half of the available roofs, and if half of the passenger vehicle owners replace their ICEVs with EVs by 2030 and use 26kWh (50%) of the EV battery capacity coupled with the rooftop Solar PV, then the concept can:

- Save 1.1 million tons of CO₂eq emissions (47%) from electricity generation and passenger vehicle transportation per year.
- Generate 5.9TWh of the 13.9TWh total annual demand (not only residential demand) for Marseille (an energy sufficiency of 42%).
- Be a potentially worthwhile investment with a payback period of 2.1 years, an LCOE of €0.027/kWh, and an NPV of €11.5 billion without a feed-in tariff by 2030.

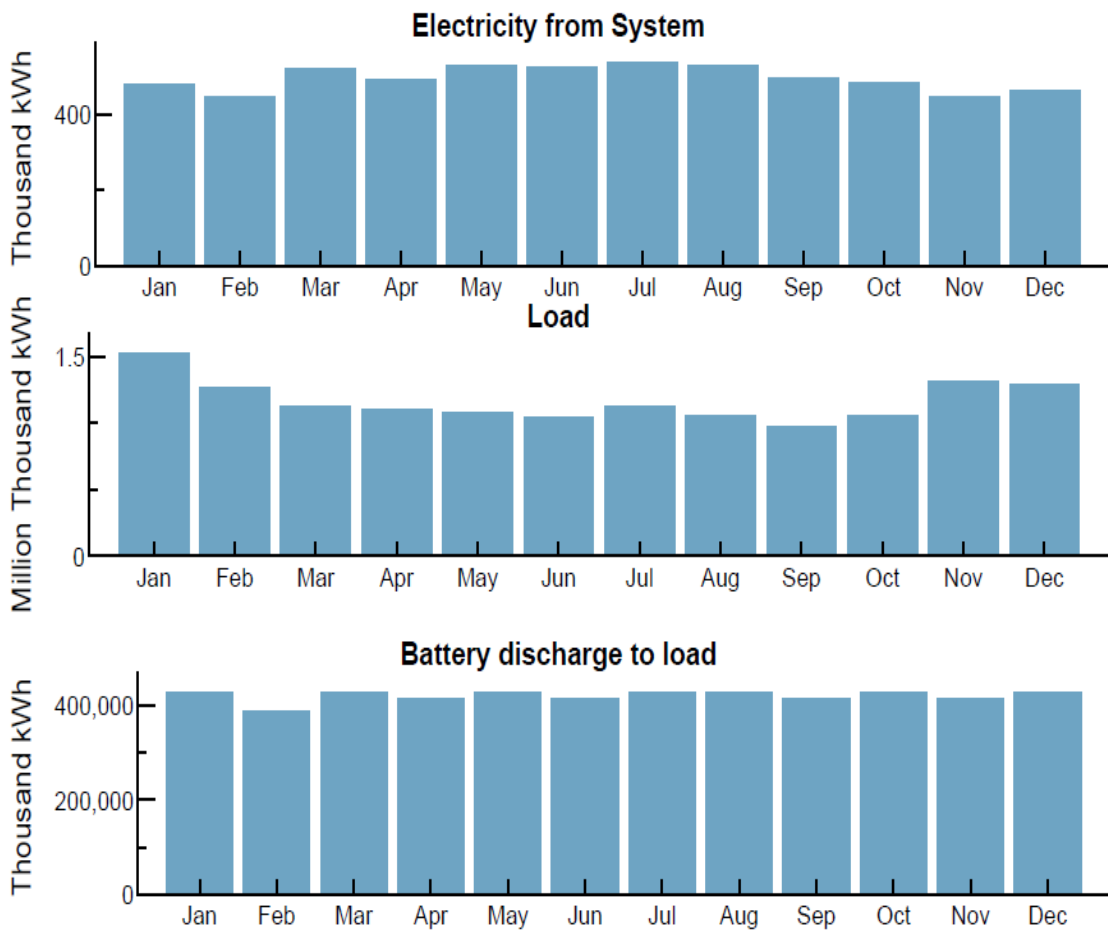


Figure 10: Simulation results of the monthly generation & load summary of the solar PV and EV generation & total load for Marseille

- *Lyon*

Our result shows that if rooftop solar PV is installed on half of the available roofs, and if half of the passenger vehicle owners replace their ICEVs with EVs by 2030 and use 26kWh (50%) of the EV battery capacity coupled with the rooftop Solar PV, then the concept can :

- Save about 874,000 tons of CO₂eq emissions (44%) from electricity generation and passenger vehicle transportation per year.
- Generate 2.3TWh of the 8.6TWh total annual demand (not only residential load) for Lyon (an energy sufficiency of 26%).
- Be a potentially worthwhile investment with a payback period of 3 years, an LCOE of €0.037/kWh, and an NPV of €5.9 billion without a feed-in tariff by the year 2030.

By coupling rooftop PV+EV in 2030, all the indices significantly improve compared to the ‘PV only in 2019’ and ‘PV only in 2030’ systems. Therefore, our findings suggest that coupling PV+EV can be a cost-effective strategy to decarbonise the energy and transport sectors in Paris, Marseille, and Lyon, France. Our findings further corroborate results in the literature for the case studies in some Japanese and Chinese cities (Kobashi et al., 2020; 2021). Related research coupling rooftop solar photovoltaics (PV) and batteries to power electric buses also finds that it is a feasible approach to reduce carbon emissions and tackle air pollution in high-density cities like Hong Kong (Ren et al. 2022). The transition to renewables will lessen the overall pollution in the long run (Hossain et al. 2023).

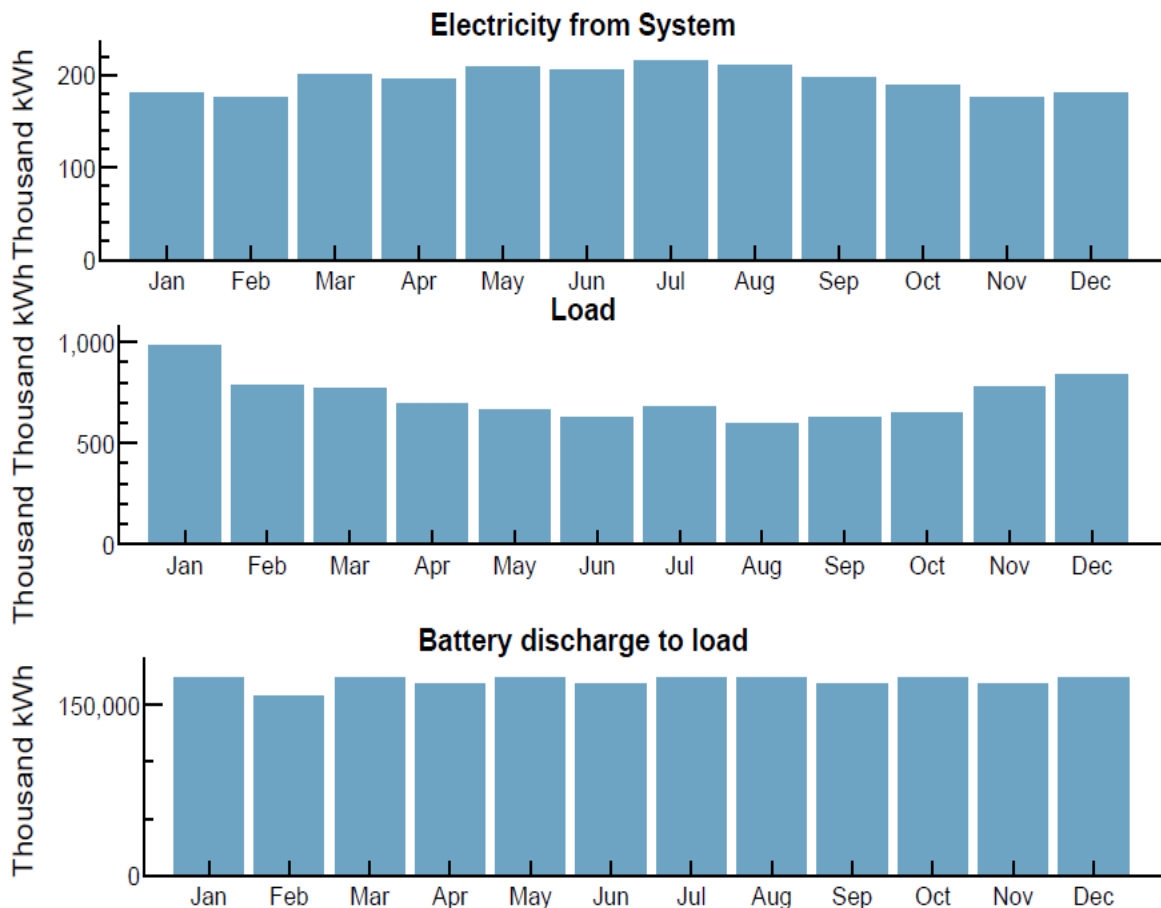


Figure 11: Simulation results of the monthly generation & load summary of the solar PV & EV generation & total load for Lyon

The results improve progressively for the scenarios with the feed-in tariff (Table 4.4 to 4.6) compared to those without the feed-in tariff. Notably, the LCOE becomes negative in the ‘PV+EV with 2030 projected pricing’ case (Table 4.6). This result strengthens the argument that the concept should not require a feed-in tariff by 2030. In addition to installing rooftop solar PV on half of the available roofs, we also analyse the results of installing solar PV on all the available rooftops in the cities (a best-case scenario)¹⁴ in Annex A.

4.1 Sensitivity analysis

We conduct a sensitivity analysis on key variables in the ‘PV+EV in 2030 without a feed-in tariff’ scenario, such as battery bank size, battery cost, solar PV module price, maintenance cost, inflation, and discount rate. We increase and decrease the input value by 20% to assess the impact of the input variables on NPV for the three cities (Table 5). The NPV is most sensitive to the discount rate, followed by the inflation rate.

For Paris, a 20% increase in discount rate decreases the NPV by 2.56%, whereas a 20% decrease increases the NPV by 2.77%. For the inflation rate, a 20% increase decreases the NPV by 1.82%, whereas a 20% decrease increases the NPV by 1.92%. A 20% increase in the battery bank size decreases the NPV by 1.5%, whereas a 20% decrease increases the NPV by 1.46%. A 20% increase in the battery price decreases the NPV by 1.58%, whereas a 20% decrease increases the NPV by 1.58%. A 20% increase in the PV module price

¹⁴ In the best-case scenario, we also use 70% of the rooftop space to account for the shading and the legal and regulatory constraints.

decreases the NPV by 0.23%, whereas a 20% decrease increases the NPV by 0.23%. A 20% increase in the maintenance cost decreases the NPV by 0.43%, whereas a 20% decrease increases the NPV by 0.43%.

Table 5: Sensitivity analysis

Paris			Marseille			Lyon		
	NPV (€)	Change %		NPV (€)	Change %		NPV (€)	Change %
Batt_bank_size (GWh)			Batt_bank_size (GWh)			Batt_bank_size (GWh)		
7.70 (-20%)	19,389	1.46	2.71 (-20%)	11,673	0.66	2.42 (-20%)	6,060	1.49
9.62	19,111	0.00	3.39	11,596	0.00	3.03	5,971	0.00
11.54 (+20%)	18,825	-1.50	4.07 (+20%)	11,510	-0.74	3.64 (+20%)	5,880	-1.53
Battery_per_kWh (\$/kWh)			Battery_per_kWh (\$/kWh)			Battery_per_kWh (\$/kWh)		
117.6 (-20%)	19,413	1.58	117.6 (-20%)	11,702	0.92	117.6 (-20%)	6,067	1.60
147	19,111	0.00	147	11,596	0.00	147	5,971	0.00
176.4 (+20%)	18,808	-1.58	176.4 (+20%)	11,489	-0.92	176.4 (+20%)	5,876	-1.60
Module price (\$/Wdc)			Module price (\$/Wdc)			Module price (\$/Wdc)		
0.22 (-20%)	19,154	0.23	0.22 (-20%)	11,628	0.28	0.22 (-20%)	5,984	0.22
0.27	19,111	0.00	0.27	11,596	0.00	0.27	5,971	0.00
0.32 (+20%)	19,067	-0.23	0.32 (+20%)	11,563	-0.28	0.32 (+20%)	5,958	-0.22
Maintenance cost (\$/kW-yr)			Maintenance cost (\$/kW-yr)			Maintenance cost (\$/kW-yr)		
23.2 (-20%)	19,192	0.43	23.2 (-20%)	11,656	0.52	23.2 (-20%)	5,996	0.41
29	19,111	0.00	29	11,596	0.00	29	5,971	0.00
34.8 (+20%)	19,029	-0.43	34.8 (+20%)	11,535	-0.52	34.8 (+20%)	5,947	-0.41
Inflation_rate (%/year)			Inflation_rate (%/year)			Inflation_rate (%/year)		
1.6 (-20%)	19,477	1.92	1.6 (-20%)	11,906	2.68	1.6 (-20%)	6,084	1.89
2	19,111	0.00	2	11,596	0.00	2	5,971	0.00
2.4 (+20%)	18,763	-1.82	2.4 (+20%)	11,301	-2.54	2.4 (+20%)	5,864	-1.80
Discount_rate (%/year)			Discount_rate (%/year)			Discount_rate (%/year)		
2.4 (-20%)	19,641	2.77	2.4 (-20%)	12,047	3.89	2.4 (-20%)	6,135	2.74
3	19,111	0.00	3	11,596	0.00	3	5,971	0.00
3.6 (+20%)	18,620	-2.56	3.6 (+20%)	11,178	-3.60	3.6 (+20%)	5,820	-2.54

For Marseille, a 20% increase in discount rate decreases the NPV by 3.60%, whereas a 20% decrease increases the NPV by 3.89%. For the inflation rate, a 20% increase decreases the NPV by 2.54%, whereas a 20% decrease increases the NPV by 2.68%. A 20% increase in the battery bank size decreases the NPV by 0.74%, whereas a 20% decrease increases the NPV by 0.66%. A 20% increase in the battery price decreases the NPV by 0.92%, whereas a 20% decrease increases the NPV by 0.92%. A 20% increase in the PV module price decreases the NPV by 0.28%, whereas a 20% decrease increases the NPV by 0.28%. A 20% increase in the maintenance cost decreases the NPV by 0.52%, whereas a 20% decrease increases the NPV by 0.52%.

For Lyon, a 20% increase in the discount rate decreases the NPV by 2.54%, whereas a 20% decrease increases the NPV by 2.74%. For the inflation rate, a 20% increase decreases the

NPV by 1.80%, whereas a 20% decrease increases the NPV by 1.89%. A 20% increase in the battery bank size decreases the NPV by 1.53%, whereas a 20% decrease increases the NPV by 1.49%. A 20% increase in the battery price decreases the NPV by 1.6%, whereas a 20% decrease increases the NPV by 1.6%. A 20% increase in the PV module price decreases the NPV by 0.22%, whereas a 20% decrease increases the NPV by 0.22%. A 20% increase in the maintenance cost decreases the NPV by 0.41%, whereas a 20% decrease increases the NPV by 0.41%.

It is worth noting that in a case when there is a mix of EVs with different battery capacities and costs, the higher the battery capacities and EV costs above Renault Zoe, the higher the cost of EV battery plus V2H system costs from the mix of EVs will be above €147/kWh, then, the lower the NPV (if other exogenous variables remain unchanged). This insight can be inferred from the sensitivity analysis.

5. Discussion

This section discusses the potential challenges to implement the rooftop solar PV+EV concept and how to overcome them.

5.1 User acceptance and behaviour (driving and charging patterns)

The success of the rooftop solar PV+EV project depends on user acceptance and willingness to participate in the project by adapting to the necessary driving and charging patterns. First, the existing ICEV owners need to be willing to replace their ICEVs with EVs and participate in the project. Second, in the collective/shared buildings that represent 44% of the residential buildings in France, there needs to be good coordination among the residents to collaborate to achieve the project's benefits. Planning EV charging and discharging times in the collective housing will require cooperation and commitment from residents to manage the EV intermittency challenge. In our model, we use a daily charging time of 3 hours. This time should logically be between 7 am and 7 pm and preferably in the afternoon at the peak of solar irradiation. In other words, EV owners should be willing to make their EVs available during the day. The efficiency of PV+EV system hinges on some cooperation between different participants in the system. The required collaboration becomes crucial where potential EV+PV synergy is the highest (Hoarau and Perez, 2018). Therefore, coordinated EV charging and discharging is important since the final reduction in electricity bills is tied to the charging and discharging strategies (Gomes et al, 2021). The realisation of the synergy will depend on the readiness of several agents to cooperate since the PV+EV synergy comes at some investment, transaction and learning costs (Hoarau and Perez, 2018).

Third, the driving and charging patterns are affected by different factors such as the purpose of driving (commuting or others), driving behaviour (aggressive drivers have lower energy efficiency), and driving conditions (topography, road congestion, outside temperature) (Venegas et al, 2021). Therefore, EV owners need to be willing to make the necessary adaptation(s). With the market now offering several energy management technology products, such as Eco-Smart and Quasar (from Wallbox), Nichicon V2H system, and r16¹⁵ from dcbel to facilitate the process, coordination can be better managed, but it still requires some willingness and commitment from the EV owners.

¹⁵ Dcbel's r16 home energy station combines solar energy conversion, EV charging, V2H backup power, and energy automation.

5.1.1 A promising future for the rooftop solar PV+EV concept

The ongoing digitalisation facilitating the automation of many jobs should be a significant catalyst for adopting the rooftop solar PV+EV concept by 2030. For example, independent/remote workers (freelancers) offering their services on technology-enabled digital platforms and industrial automation are both growing trends that will lead to many people teleworking by 2030. Teleworking should facilitate charging and discharging coordination as more and more people work from home. As of December 2021, 34.5% of employees in French companies teleworked. The most common frequency of teleworking is two days per week, followed by three days per week for all French employees (Statista 2021e, Statista 2021f).

Furthermore, one of the EU's top three policy priorities for transport is to increase teleworking (as an opportunity to reduce commuting). According to a European Investment Bank survey (EIB, 2021), 38% of French people accept teleworking as a climate change mitigation strategy. Moreover, from September 2021, the French government is incentivising teleworking with a lump sum allowance to compensate for teleworking in the civil service. The amount of the "telework lump sum" is set at €2.5 per day up to a limit of €220 per year (i.e., 88 working days per year) (French Law, 2021). Therefore, the rooftop solar PV+EV concept can have a promising future as a higher percentage of people (including EV users) are expected and incentivised to telework. Teleworking should provide more opportunities to coordinate daytime charging and discharging of EVs by 2030. Furthermore, the government can also use other policies to incentivise other behavioural changes and adaptation among EV users' (Venegas et al, 2021).

5.2 The lack of a joint policy to accelerate rooftop solar PV+EV

Since the rooftop PV+EV can achieve an LCOE as low as 4 c€/kWh compared to around 18c €/kWh of the current household electricity tariff, it is worthwhile for the government to support this concept with the right policies. However, there are separate government policies supporting rooftop solar PVs and EVs. The immense opportunity to decarbonise with rooftop solar PV+EV warrants a combined policy to support both solutions. First, the policy should be designed to promote the solution. Second, the policy needs to coordinate the different stakeholders in the ecosystem. Electric mobility is in a broad ecosystem with various actors from the transport (vehicle, battery and charging infrastructure OEMs) and electric systems (regulatory authorities, market traders, electric utilities, and service providers etc.) (Perez and Arowolo 2021b). Therefore, the government policy needs to coordinate the actors such as the EV users, EV, solar PV, and V2H original equipment manufacturers (OEMs), urban planning, standardisation bodies, distributed system operator (DSO), regulatory authorities, and public transport operators and authorities.

Third, the government policy needs to facilitate project development, planning, execution, monitoring, and control with the participating EV owners, other investors (private, public, and institutional), and the finance institutions (banks, insurance companies). Fourth, the government policy needs to facilitate user acceptance and induce behavioural changes/adaptations for both solutions. Fifth, the government needs to implement policy to support the market development of V2H smart charging solutions. Sixth, the regulator needs to support EV users via the required regulatory adaptations and reform of existing regulations. The government-initiated policy incentives (for both EVs and charging infrastructure) need to be continued for the EV market to mature (MIT, 2019). Market design

rules, regulations, and government policies should attempt to resolve the challenges of PV+EV interactions (Perez and Arowolo, 2021a).

Seventh, combining incentives for renewables and energy efficiency in the built environment is a meaningful way to achieve efficient and resilient solutions while creating local jobs and driving rapid economic recovery in the labour-intensive construction/building sector, which is a driver for the entire economy. Incentives for distributed PV on buildings are cost-effective when combined with building renovations and investments in energy efficiency, distributed energy resources (such as EVs), and charging infrastructure (IEA, 2021a). For example, the holistic combination of the solar PV installation premium, EV ecology bonuses/subsidies, ADVENIR¹⁶ for charging infrastructure installation, and MaPrimeRénov should provide better outcomes (French government, 2020a; b; c; d).

5.3 The fear of battery degradation

The fear of battery degradation could make EV owners reluctant to partake in solar PV+EV projects (Perez and Arowolo, 2021b). Battery degradation can cause capacity loss over time, which may impact an EV's range capability (Noel et al, 2019). A battery's all-life capacity fade due to degradation is from calendar ageing and cycle ageing effects. Calendar ageing depends on time and temperature, while cycle ageing depends mainly on the number of charge/discharge cycles. The degradation mechanism occurs faster when the battery has a high energy density, increasing with a higher state of charge and temperature (Thompson, 2018). Research findings from (Nuvve, 2021; Marinelli, 2020) suggest that with the average temperature in France, an EV battery should last for the 20 years project period with an optimal home charging strategy. This finding suggests that battery degradation fear may be overstated. Therefore, there is a need for awareness and education campaigns to allay the fear of battery degradation for EV owners willing to participate in the project.

5.4 The lack of a standardised building-EV interface

A standardised building-EV interface needs to be defined and set up. The development of standardised charging/discharging cables and piping systems, according to the technical characteristics of the integrated EVs, is essential for real-life applications (Zhou et al, 2019). The French Mobility Orientation Law ('LOM Law') has taken some steps in this direction. The LOM law makes it an obligation to pre-fit electric charging points in car parks of ten or more spaces in new/renovated buildings by 2025. The LOM Law has also created a right to take charge of collective housing and simplified voting rules for work on the electrical installation of charging stations in condominiums (LOM law, 2019). However, the government could extend the LOM Law to other types of residential buildings (old and not under renovation) to ensure a standardised building-EV interface in all residential buildings by 2030.

5.5 The lack of awareness and understanding of rooftop solar PV+EV and V2H solutions

There is a need for increased public awareness and education on rooftop solar PV+EV and V2H solutions as potential game changers to decarbonise transport and power sectors concurrently. The awareness campaign should focus on the environmental benefits (i.e., mitigating climate change) and the economic benefits (i.e., electricity cost reduction/savings).

¹⁶ The ADVENIR program covers the costs of supplying and installing charging points up to 30% for private car parks intended for fleets until December 31, 2021, 60% for car parks open to the public until March 31, 2022, and 50% for collective residential charging points.

5.6 The impact of other emerging technologies

Decarbonisation brings new actors into the market and increases the need for grid coordination and management (Papadis and Tsatsaronis, 2020). Emerging technologies (such as minigrid, vehicle-to-grid, and blockchain) could impact the PV+EV synergy and force grid operators to readjust their grid management methods (Gomes et al, 2020). The policy should therefore consider the impact of emerging technologies on the rooftop solar PV+EV concept.

5.7 The impact of rooftop solar PV+EV on electric utilities' revenue (demand disruption, sunk network infrastructure costs recovery, and stranded assets)

The rooftop solar PV+EV concept could increase the risk of stranded assets for electric utilities. As more EV users participate in the project, there is expected to be less demand for the grid power supply (i.e., demand disruption). More people are expected to defect from the grid either partially or totally. The shift to rooftop solar PV+EV could reduce the revenue of the existing power plants, which means that some producers may be unable to recover their investments (Yu, 2018). Besides, market structure changes could impact utilities' revenue and lead to a situation where power generation assets are stranded before the end of their lifetime (Papadis and Tsatsaronis 2020).

There is also the ensuing problem of recovering the (sunk) network infrastructure costs. About 28% of the current electricity tariff in France (around c€5/kWh) is for grid funding (Yu, 2018). Therefore, an optimal tariff design is required to recover costs, which makes it essential to understand what network tariff structure will recover grid costs and facilitate rooftop solar PV+EV synergy. This is the debate on tariff structure/design (vis-à-vis efficiency and equity issues and the trade-offs) and grid cost recovery. Several factors affect the grid cost structure, making assumptions about the cost structure challenging. For instance, the network operator needs to recover different costs, from fixed operating costs and sunk capital costs to variable operating costs and the cost of network losses (Gomes et al, 2021b)

First, it appears paramount for the regulator to centrally coordinate the uncoordinated decisions of rooftop PV+EV users' partial or total grid defection. A lack of coordination can cause an overall efficiency loss when network tariffs are designed incorrectly (Schittekatte et al. 2018). Second, regulations should focus on the cost-efficient use of existing infrastructure and the replacement and reinforcement of infrastructure investments and consider innovation (Schittekatte et al. 2021). Third, changing regulations could create winners (that may escape the network charges) and losers (that have to bear the network costs) (Hoarau and Perez, 2019). Given that the standard network tariff design methods do not suffice to transfer some of the welfare gains of the active consumers (involved in the PV+EV project) to the passive ones, other solutions are needed to achieve fairer outcomes. In theory, the lowest distribution network tariff comprises a fixed part for the sunk costs and a capacity part for the grid investment costs. However, the capacity part can be partly avoided if it is cheaper for consumers to invest in variable energy resources. Therefore, a three-part tariff that combines fixed, capacity, and volumetric charges may be appropriate (Schittekatte and Meeus, 2020). There appears to be rising consensus in the literature in favour of this type of tariff design (energy/volumetric charge plus the fixed and peak capacity charge to recover the network costs) (Sioshanshi, 2016, Dameto et al, 2020, Schittekatte and Meeus, 2020). This could be a path forward to strike a balance between cost efficiency and equity in tariff design to achieve a simple, transparent, economically efficient and predictable outcome.

A promising policy choice could be for EV users engaged in the rooftop PV+EV project with a volumetric tariff (without net metering) to pay the electric utilities a certain percentage of their actual savings as a fixed charge for a pre-determined period to facilitate network cost recovery. EV users should also pay some percentage of the capacity charge for future network operations and expansion (if applicable) to create a win-win situation. This payment should be the difference between the projected/actual savings of the EV users and the avoided costs of the system, i.e., the electric utility's unrecovered revenue due to the presence of the rooftop PV+EV system (Gomes et al, 2021a). In other words, EV users' could use part of their savings to pay the avoided cost of the system as a fixed/capacity charge. From the outset, the thinking on cost saving to compensate for the avoided costs should be considered in the project finance model. As shown in this paper, if EV users can achieve about 4c€/kWh, then it should not be hard to sell them the idea of paying part of the 5c€/kWh of the network recovery cost, given that the current market rate is 18c€/kWh. In theory, this approach should not deter investment and public acceptance, but it could prove challenging in practice. In sum, there is no perfect approach to increasing the revenues of electric utilities. Policymakers will have to face a fundamental trade-off between economic efficiency and equity (Borenstein, 2016).

5.8 The need for demonstration projects

There is a need for investment in demonstration projects to validate the technical, economic, and environmental benefits of the rooftop solar PV+EV analysed in this paper to facilitate large-scale deployment in cities. It will be of particular interest to see how the system can be optimised to handle real-time flexible loads. For example, how will the system meet the heating power demand in the winter months? Moreover, demonstration projects should help to increase understanding of how flexible operations can influence the quality of the building services and the occupant's satisfaction/productivity (Li et al. 2021).

Table 6 summarises the implementation challenges and our recommended solutions.

Potential implementation challenges	Proposed solutions
User acceptance and behaviour (driving and charging patterns)	Organise educational outreach programs for ICEV owners on the benefits of replacing their ICEVs with EVs and participating in the project. Proper coordination among residents to work together to achieve the benefits of the project EV owners should be willing to make the necessary adaptation(s) to their driving and charging patterns.
The lack of a joint policy to accelerate rooftop solar PV+EV	Recognise the immense opportunity to decarbonise with rooftop solar PV+EV concurrently. Consider enacting policies to coordinate the different stakeholders in the ecosystem. Consider enacting policies to facilitate project development, planning, execution, monitoring, and control with participating EV owners/other stakeholders. Consider enacting policies to facilitate user acceptance and induce behavioural change/adaptation. Consider enacting policies to support the development of V2H smart charging solutions. The regulator should support with the needed regulatory adaptations/reform of existing regulations.

The fear of battery degradation	Create public awareness campaigns to allay EV owners' fear of battery degradation
The lack of a standardised building-EV interface	Define and set up a standard building-EV interface Develop standardised charging/discharging cabling and piping systems Extend the LOM Law to old residential buildings (not under renovation) to achieve a standardised building-EV interface in all residential buildings by 2030. Remove the legal and regulatory constraints on the PV+EV concept.
The lack of awareness and understanding of rooftop solar PV+EV and V2H solutions	Commence public awareness campaigns on the environmental benefits and economic benefits for households in terms of electricity cost reduction/savings
The impact of other emerging technologies	Allay EV owners' fear of battery degradation
The impact of rooftop solar PV+EV on the electric utilities' revenues (demand disruption, recovery cost of sunk network infrastructure cost, and stranded assets)	The regulator should orchestrate centralised coordination to avoid uncoordinated partial or total grid defection decisions by rooftop PV+EV users' Regulatory reforms should consider innovation.
The need for demonstration projects	Consider investing in demonstration projects to validate the economic and environmental benefits of the rooftop solar PV+EV concept.

Table 6: Implementation challenges facing rooftop solar PV+EV and potential solutions

6. Conclusion

France's effort to meet its EU 'Fit for 55' set targets by 2030 will require innovative solutions that can facilitate rapid multi-sector decarbonisation and simultaneously address the energy trilemma challenge. This paper attempts to contribute to this debate with a potential solution for France's energy, transport, and building sectors. We analyse the rooftop solar PV+EV decarbonisation potentials for residential buildings in France using SAM to run city-scale simulations for Paris, Marseille, and Lyon. We also build a model to compute CO₂ emission reduction. We model 3 scenarios: 'PV only with 2019 pricing', 'PV only with 2030 projected pricing', and 'PV+EV with 2030 projected pricing'. For each of the three scenarios, we consider four cases: (1.) with a feed-in tariff, (2.) without a feed-in tariff, (3.) with utilisation of half of the technically available rooftop space and (4.) with utilisation of all the technically available rooftop space. We then go on to discuss the system's impact using five indices: (a) NPV, (b) levelised cost of energy (LCOE), (c) payback period, (d) energy sufficiency, and (e) CO₂ emissions reduction.

Our results show that rooftop solar PV+EV is a promising pathway that can be a potential game-changer to decarbonise France's energy, transport and building sectors simultaneously. Coupling rooftop solar PV+EV can meet 19%, 26%, and 42% of the electricity demand (if half of the available rooftop space area is utilised and half of the passenger vehicle owners replace their ICEVs with EVs by 2030) in Paris, Lyon, and Marseille, respectively. Moreover, coupling rooftop solar PV+EV can provide a low LCOE of €0.037/kWh, a payback period of 2-3 years, an NPV of €6-19billion, and a CO₂ emissions reduction of 44%-48% without feed-in tariffs in the three cities. Coupling rooftop PV with EV significantly improves all the indices compared to the 'PV only in 2019 or 2030' system. Therefore, our results suggest that rooftop solar PV+EV can be a cost-effective strategy to decarbonise the energy and transport system concurrently in France's most populous cities. Furthermore, we conduct a sensitivity

analysis on key variables in the PV+EV in 2030 without a feed-in tariff scenario. The NPV is most sensitive to the discount rate and inflation rate. A 20% increase in the discount rate or inflation rate decreases the NPV by over 1.5%.

Our overall contribution to the PV+EV coupling debate is as follows: i. Using two commonly used vehicle models in France, we discuss how to design the PV+EV concept for the combined decarbonisation of transport, energy and building sectors. ii. We build a model to compute CO₂ emission reduction of the rooftop solar PV+EV concept in France. iii. We provide insight into the market design and regulatory issues of the rooftop solar PV+EV concept in the French context. iv. We provide deep insight and analysis on the implementation challenges of the rooftop solar PV+EV concept stemming from theoretical models to real-life implementation in France. The following are our overall policy recommendations from our models and analyses of the implementation challenges:

- The government should consider enacting combined policies to accelerate the deployment of rooftop solar PV+EV as a decarbonisation pathway. The government should strengthen and support rooftop solar PV+EV penetration policies.
- The government should consider enacting policies to coordinate the different stakeholders in the ecosystem, facilitate user acceptance, induce behavioural change/adaptation, and increase public awareness.
- Planning at the metropolitan level should support coupling rooftop solar PV+EV.
- The government should consider investing in demonstration projects to validate the economic and environmental benefits of the rooftop solar PV+EV concept.
- The regulator should orchestrate centralised coordination to avoid the uncoordinated partial or total grid defection reactions of rooftop solar PV+EV users.
- Expansion of rooftop solar PV+EV will lead to a change in power demand from electric utilities. Pricing/tariff design decisions should therefore consider rooftop solar PV+EV expansion.
- Regulatory reforms should consider innovation with rooftop solar PV+EV.

6.1 Limitations and future research work

A limitation of this research is that our assumptions, such as the projected installed cost of rooftop solar PV, cost of EV+V2H system, projected cost of EV and ICEV may overestimate or underestimate the exogenous input data in our model. The values could be higher or lower and thus impact our results. Although our techno-economic analysis includes a sensitivity analysis to understand these impacts, there is still a need for caution. Furthermore, a geopolitical crisis could impact our model/results, such as commodity price changes that could trigger inflation with significant macroeconomic impacts. For example, the Russia-EU/NATO energy supply/demand imbroglio. These limitations should be kept in mind when using our findings for decision-making.

Moreover, this research has not compared the rooftop solar PV+EV concept with other decarbonisation options. Therefore, we do not conclude that the rooftop solar PV+EV concept is the “first-best” solution. Although price of PV and EV systems in a given year may be dynamic, we use yearly price forecast to minimise the complexity of our models. Further research could focus on data analysis on a granular level per city. For example, how many buildings per city are residential, the load profile analysis, the ratio of the single owner to collective buildings, and how to meet the demand for space heating in the winter months. Finally, research on the multi-sector decarbonisation with rooftop PV+EV for the electricity, transport, and building sectors warrants further study.

Author contributions

Wale Arowolo: Conceptualisation; Methodology; Investigation; Data curation; Formal analysis, Validation; Visualisation; Writing - Original draft; Writing - Review and editing.

Yannick Perez: Conceptualisation; Methodology; Funding acquisition; Project administration; Supervision.

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Annex A

'PV only" in 2019 (Without FIT)	Paris	Marseille	Lyon
NPV (\$Million)	-1,067.80	1,881.56	161.28
Energy sufficiency (%)	3.63%	12.85%	6.38%
CO2 emission reduction (Tonnes)	79,350.47	102,517.45	31,615.62
Payback Period	16.1 years	8.6 years	11.5 years
LCOE (€/kWh)	0.36	0.21	0.27
IRR (%)	-20.34	48.25	10.25
'PV only" in 2030 (Without FIT)			
NPV (\$Million)	610.11	3128.10	664.06
Energy sufficiency (%)	3.63%	12.85%	6.38%
CO2 emission reduction (Tonnes)	46,945.57	60,651.68	18,704.53
Payback Period	10.8 Years	5.8 years	7.8 years
LCOE (€/kWh)	0.26	0.15	0.19
IRR (%)	17.30	119.43	62.85
"PV + EV" in 2030 (Without FIT)			
NPV (\$Million)	29,949	18,766	9,326
Energy sufficiency (%)	39.14%	80.49%	53.34%
CO2 emission reduction (%)	47.65%	56.77%	50.55%
CO2 emission reduction (Tonnes)	2,855,374	1,206,944	897,353
Payback Period	2.3 years	2.2 years	2.2 years
LCOE (€/kWh)	0.030	0.029	0.029
IRR (%)	294.73	413.04	296.62
'PV only" in 2019 (With FIT)			
NPV (\$Million)	-1.06	3,716.14	726.88
Energy sufficiency (%)	3.63%	12.85%	6.38%
CO2 emission reduction (Tonnes)	79,350.47	102,517.45	31,615.62
Payback Period	11.2 years	5.5 years	7.3 years
LCOE (€/kWh)	0.273	0.120	0.184
IRR (%)	-0.02	95.30	46.21
'PV only" in 2030 (With FIT)			
NPV (€Million)	2,029.16	4,962.68	1,229.66
Energy sufficiency (%)	3.63%	12.85%	6.38%
CO2 emission reduction (Tonnes)	46,945.57	60,651.68	18,704.53
Payback Period	6.7 years	3.7 years	4.9 years
LCOE (€/kWh)	0.171	0.062	0.107
IRR (%)	57.55	189.47	116.39
"PV + EV" in 2030 (With FIT)			
NPV (€Million)	45,508.87	30,392.85	14,103.69
Energy sufficiency (%)	39.14%	80.49%	53.34%
CO2 emission reduction (%)	47.65%	56.77%	50.55%
CO2 emission reduction (Tonnes)	2,855,374	1,206,944	897,353
Payback Period	1.1 years	1.1 years	1.1 years
LCOE (€/kWh)	-0.06	-0.05	-0.05
IRR (%)	519.23	715.99	521.78

ANNEX B

Solar resource data of Paris, Marseille and Lyon